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ACCURACY OF IN-SITU WATER-TO-CEMENT METERS FOR CONCRETE

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Utah Department of Transportation
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16. Abstract
Concrete's water to cementitious (w/cm) ratio is the most important indicator of the overall strength and durability of the structure. A method to determine the w/cm ratio on-site is important and needed for quality assurance and quality control. There are currently limited standardized techniques for the measurement of w/cm on-site and those techniques can be very time consuming. A developed in-situ microwave moisture meter exists that relies on the difference in the dielectric constant of concrete from that of water to estimate the w/cm ratio. In this report, the accuracy and precision of the meter is studied. Several paste, mortar, and concrete mixes with known w/cm ratios as well as aggregates with known moisture contents were measured with the Cementometer™ device. An AASHTO T318-02 microwave test was also performed in comparison to the Cementometer™ on known w/cm values.

Statistical methods included a t-test determining the accuracy of the device. For precision, linear regression analysis, absolute difference, and sum of squared error calculations were made between the Cementometer™ predicted w/cm and actual w/cm contents of the mixtures. Overall, the Cementometer™ device was found to precisely measure moisture levels in aggregates, but in concrete none of the modes were precise (all R^2 values were less than 0.065) nor accurate (p-value less than 0.044). On the other hand, the in-lab AASHTO microwave method produced statistically precise (R^2 of 0.62 or more) and accurate (p-value of 0.91) readings; and thus the in-lab AASHTO T318-02 method is recommended over the in-situ Cementometer™ for w/cm ratio determination.

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EXECUTIVE SUMMARY

A study to determine the accuracy of the in-situ microwave moisture meter Cementometer™ was performed. The meter tested is said to measure the dielectric constant of a concrete mixture and correlate the constant to the water to cementitious ratio (w/cm). The meter can be calibrated to specific mix designs or the user has the option of selecting pre-calibrated settings for w/cm measurement. A fourth option is a direct reading (raw number) that is recorded by the meter's internal software while calibrating in order to generate a correlation between the w/cm and direct reading. A total of 157 concrete mixtures with a range of w/cm from 0.30 to 0.55 were tested. The meter was also tested on cement paste, mortar and sand mixtures. Six statistical methods to determine the accuracy of the meter were performed. The Cementometer™ correlated to the moisture level of sand mixtures and was found precise on the sand only mixture. However, the meter rarely correlated or detected the actual w/cm of concrete mixtures.

Ways to improve the calibration and testing accuracy of the meter were tried by measuring the meter's sensitivity to factors like temperature of the mixture or type of water used. No real correlation was found between the meter's direct readings and the different factors tested. Due to the meter's inaccuracy and imprecision on tested mixtures, it is recommended to not depend on the meter for in-situ determination of the w/cm of fresh concrete. Instead, the AASHTO T-318-02 microwave oven method should be used due to its acceptable measurement of the moisture level in concrete. Although this method can take more than 15 minutes to perform and largely depends on the availability of a microwave oven on site, it was shown to be more accurate than the microwave meter alternative.

1.0 INTRODUCTION

1.1 Problem Statement

The compressive strength and w/cm ratio of concrete are the two most important indicators of its overall strength and performance. Typically, an increase in w/cm ratio results in a decrease in compressive strength and an increase in the porosity of the structure which causes early degradation of the structure (Kim et al. 2014). Although the w/cm ratio is considered a primary indicator of strength, the higher paste content and higher air content both can also decrease strength (Popovics 1990). A concrete mix design often has a specified w/cm ratio and the concrete producer would make sure the concrete meets these specifications before it leaves the batch plant. However, extra water is often added after leaving the plant, or even prior to leaving the plant, such as when the truck driver washes the concrete's chute inlet from any leftover concrete while batching. Water may also be added, for example, when a traffic delay impedes the concrete truck and keeps it from arriving at the jobsite on schedule; or water may be added to prevent the mixture from becoming too stiff for finishers to work with at the jobsite. The addition of any excess water increases the actual w/cm ratio and is a major issue with the concrete quality. For these reasons, a method to determine the in-situ w/cm ratio is important for quality control and assurance in order to avoid serious durability (Kim et al. 2014) and strength issues during the lifecycle of the structure in question.

1.2 Objectives

The primary objectives of this research study are to calibrate, test and determine the accuracy of the Cementometer^{TM} on concrete mixtures. A recommendation as to whether or not the meter should be used instead of the standard method, the AASHTO T-318-02 microwave oven method, was also given.

1.3 Scope

The Cementometer^{TM} was tested on concrete mixtures with a known w/cm in order to measure the error between the reading and the batched w/cm. Several mix designs were obtained from UDOT and were recreated to calibrate the meter at the University of Utah and at the UDOT materials labs. Some of the mixtures were tested in the labs and others were tested at the site of construction or batching. Over the course of one year, the meter was calibrated to 14 mix designs and tested over 195 times.

There were difficulties in calibrating and testing the meter over some w/cm ranges, and the meter was not found to be sensitive enough to the actual water content of the concrete mixture. The meter was also tested on sand only mixtures with the water content varying from oven dry to saturated. The meter's direct reading correlated well to the moisture level in the sand. This led the authors to believe that the meter is more sensitive to the free moisture level of the mix rather than bounded water as in the case of concrete. To determine some of the factors that might affect the meter's sensitivity and accuracy, factors such as temperature of the mix and type of water were also tested. Some of the mixtures tested by the meter were also tested according to the AASHTO T-318-02 microwave oven to compare the accuracy of the two methods.

1.4 Outline of Report

An overview of the different methods available to measure the water content of concrete and the theory behind microwave moisture meters are given in sections 2.1 through 2.4. The remainder of Section 2.0 is an overview on the methodology of the Cementometer^{TM} and the calibration process. Section 3.0 includes a statistical study on the accuracy of the meter and the results from the study on concrete mixtures. Section 4.0 reviews additional observations for using the Cementometer^{TM}. Finally, Section 5.0 concludes the results of this study and recommendations with Section 6.0 listing potential future work.

2.0 RESEARCH METHODS

2.1 Methods of Measuring Water-to-Cement Ratio

There are currently four ways for estimating the mass of water relative to the mass of cementitious materials in fresh concrete. These estimation methods are described as follows:

- Relying on the batch ticket from the concrete producer to measure and report the actual mixture weights. This method does not indicate whether or not additional water was added to the mixture after leaving the producer.

- Obtaining a field sample of fresh concrete and placing it in a nearby trailer or laboratory's microwave oven for 15 minutes according to AASHTO T 318-02 (AASHTO 2015) to quantify the water mass loss. This current standard method does not provide actual w/cm content values and largely depends on the availability of a microwave oven on site, but has been reported to have an accuracy around 5% (Rodden and Lange 2005; North Dakota Department of Transportation 2008).

- Using the NDT James Cementometer™, a handheld microwave moisture meter for the purpose of in-situ determination of w/cm ratio. The accuracy of this method will be determined from this research study.

- Waiting for concrete to harden, then taking a core sample to a petrographer with the same source cement and aggregates for them to estimate the w/cm content from matching the microstructure (Wirgot and Van Cauwelaert 1994; ASTM 2014). The petrographer method has been reported to be accurate with a p-value of 0.22 or lower (Wirgot and Van Cauwelaert 1994), however, the method depends significantly on the cement content, curing method, and physical size of the sample tested.

Of these methods, the third option involving the microwave moisture meter is fundamentally expected to be the best because it involves having a handheld device which can conveniently be inserted into any concrete and it instantaneously displays the w/cm content on the screen. The company NDT James claims the device is “accurate” (James Instruments 2010), but does not report statistics on the level of accuracy when predicting w/cm content. Michigan DOT had conducted a durability study, including measurements for w/cm contents using this Cementometer™. After performing the study in Michigan, the authors concluded that the device “does not produce results that correlate with known mix designs.” In other words, the NDT James Cementometer™ is likely inaccurate, as shown by their measurements, which are re-illustrated in Figure 2.1 (Peterson and Sutter 2011). Determining the accuracy of this device is the purpose of this report presented herein.

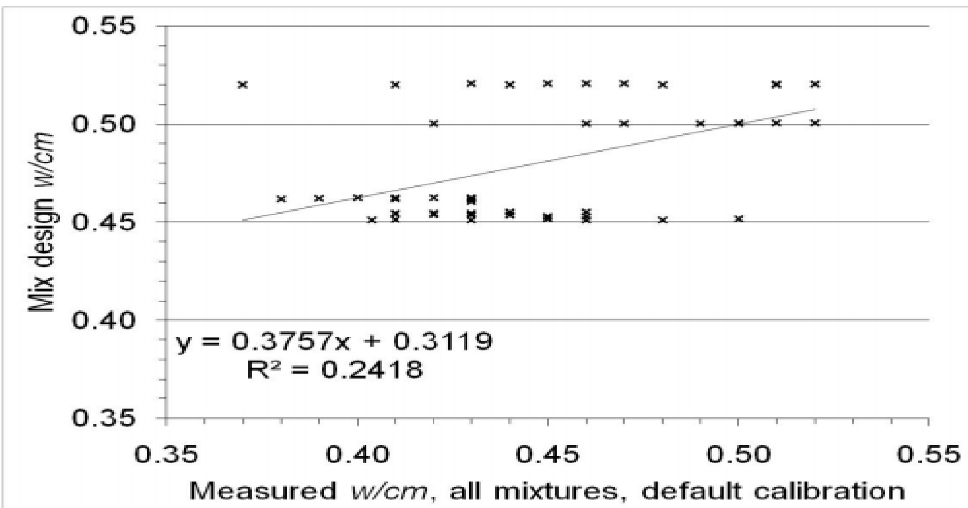

Figure 2.1 Michigan DOT Cementometer™ results for different concrete mixtures (Peterson and Sutter 2011).

2.2 Methodology of In-situ Microwave Meter

2.2.1 Dielectric Permittivity

In theory, the microwave meter operates on the principal that water has a significantly different dielectric constant compared to that of solid materials, such as cement and aggregates. As such, a microwave-based meter should be able to calculate and predict the actual free water content in the concrete. This report summarizes the theories used in dielectric moisture meters, the test results measured with the Cementometer™ for this study, and statistic calculations.

Dielectric materials are materials that become polarized when an electrical current flows through (Nave 2012). An example of a material that can be easily polarized under current flow is water. A material does not necessarily need to be conductive to be dielectric. Even non-conductive materials, such as limestone rocks, can have a dielectric constant because their randomly oriented molecules can be polarized and re-oriented under an applied electric field.

As another example, Figure 2.2 shows a schematic of a parallel plate capacitor commonly used to measure the dielectric of materials, and how the particles of a dielectric are polarized. In the microwave process, an electric charge is applied to the conductive plates (Shown in Figure 2.2) or conductive rods (as is estimated with the Cementometer™ design), which creates electric field lines in between the plates. If the area between the plates consists of a highly polarized material, the electric field lines pass in a straight path from one plate to the other. However, if the area contains a lower dielectric material, some lines may still pass unaltered to the other plate, while other field lines from the unpolarized components may follow skewed and scattered trajectories to the other plate.

a)

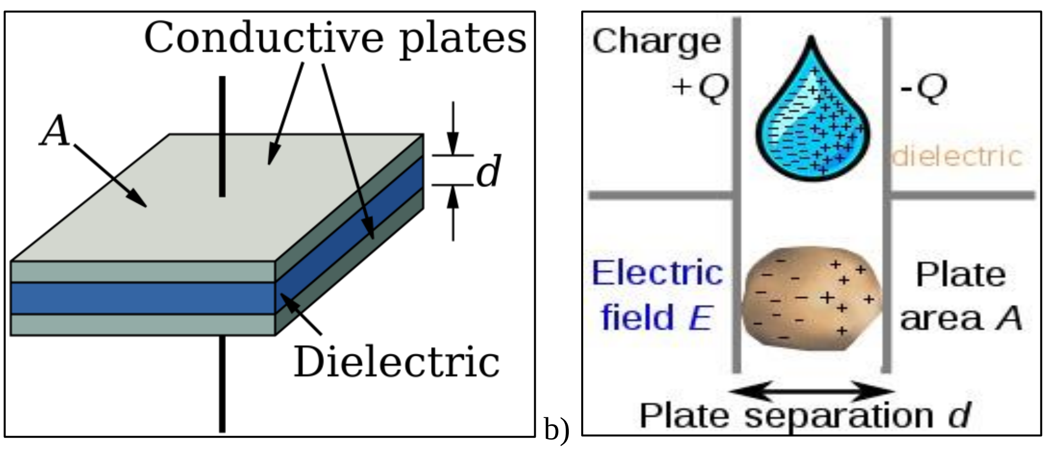

Figure 2.2 a) Parallel plate capacitor and b) polarization of a dielectric materials under an applied electric field (Wikipedia 2006).

Permittivity is the material's resistance to an encountered electrical field, or resistance to polarization. The calculated dielectric constant of that material is then the relative difference in measured permittivity with respect to the permittivity of a vacuum (shown in Equation 1) (Nave 2012). The value of the dielectric constant is also well known to be dependent on the imposed frequency and temperature during the permittivity measurement.

$$\boldsymbol{\varepsilon_r = \varepsilon_s / \varepsilon_0} \qquad \textbf{(Equation 1)}$$

where:

$\boldsymbol{\varepsilon_r}$ **=** Relative Permittivity (Dielectric Constant)

$\boldsymbol{\varepsilon_s}$ **=** Measured permittivity of material in Farad per meter (F/m)

$\boldsymbol{\varepsilon_0}$ = Permittivity of a vacuum in Farad per meter (F/m)

Water, a polar molecule, is completely polarized by an applied electric field (as illustrated in Figure 2.2. Water is commonly known to have a significantly high dielectric constant in comparison to other materials, as listed in Table 2.1. Aggregate particles, for example, are not commonly made of polar molecules, and only small portions of the material may become polarized producing a small dielectric constant. Also air is close to a vacuum and thus has a dielectric constant close to 1.

Table 2.1 Dielectric of Common Materials (Young and Freedman 2015)

Material	Minimum Dielectric	Maximum Dielectric
Water	34	78
Air	1	1
Quartz	5	5
Glass	3.8	14.5
Dry Soil	2.4	2.9

When the material is heterogeneous or comprised of multiple components, the effective permittivity is computed according to the Lichtenecker mixing rule (Wu et al. 2003) as follows in Equation 2.

$$log(\varepsilon_{composite}) = \sum[V_i * log(\varepsilon_i)] \qquad \textbf{(Equation 2)}$$

where:

$\varepsilon_{composite}$ = Effective dielectric constant of the composite material

V_i = Volume fraction of a specific component or phase

ε_i = Dielectric constant of a specific component or phase

Since the dielectric constant is a measurement of the internal charge resistance in an electric field, a current must be applied at a constant frequency. The range of frequencies between 300 MHz to 300 GHz is considered a microwave frequency (Nave 2012) and some frequencies can also be considered within the wider radio range of 3 kHz to 300 GHz. Unlike low radio frequency waves, these microwave high radio frequency electromagnetic fields generally provide more accurate material properties (Baker-Jarvis et al. 2010). The specific frequency produced by the Cementometer™ is unknown.

2.3 General Dielectric Measurements

A network analyzer and coaxial probe owned by the Department of Electrical Engineering at University of Utah was used to measure the dielectric constant of water, dry sand, and air as a function of frequency (from 200 MHz to 400 MHz). As seen in Figure 2.3, the dielectric of water can be as high as 76, compared to 0.92 for sand and air. Due to the fact that ions in the water might result in inaccurate dielectric readings, dielectric measurements for water were performed using deionized water instead of tap water. Water used to batch concrete in batching plants was with tap water, not deionized water, and thus the dielectric constant might differ slightly from the measured one in Figure 2.3. The maximum dielectic values for deionized water, providing the greatest difference compared to air and stone, were found at microwave frequencies between 280 and 300 MHz. This frequency range would be considered ideal for an effective microwave meter.

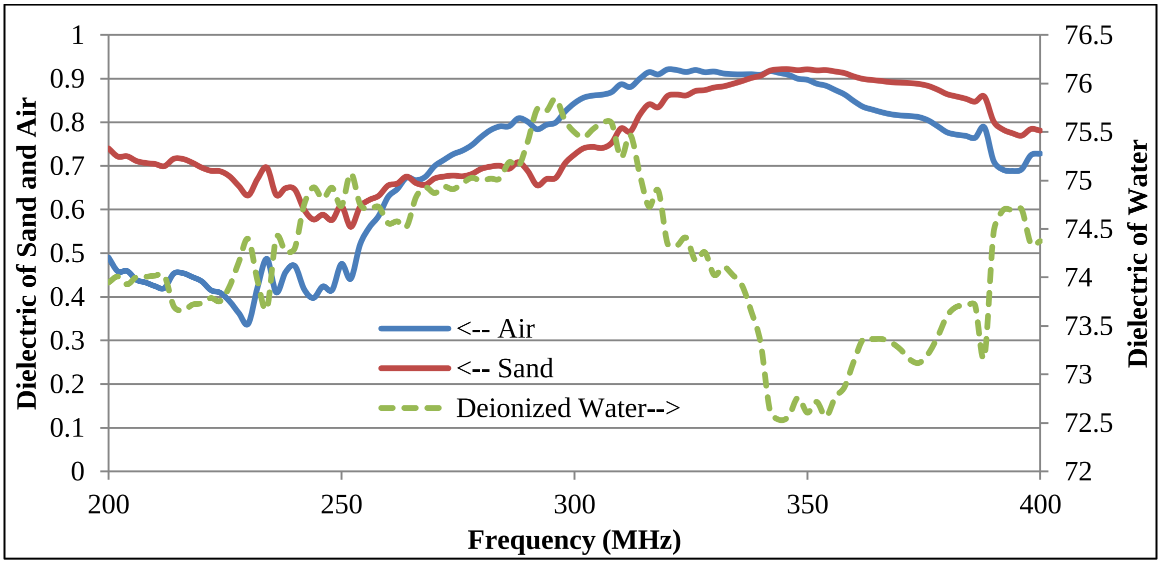

Figure 2.3 Measured dielectric constant versus frequency.

2.4 Temperature Effects

Since the theory is that the dielectric permittivity depends on temperature, it is hypothesized that temperature of the environment during the testing may affect the value on the Cementometer™. As the temperature of water increases, the dielectric constant is expected to decrease in a linear trend (Malmberg and Maryott 1956).

To test the effects that temperature has on the meter's output, two water tests were performed with deionized water and regular tap water. Only water was tested instead of an entire concrete composite and both deionized water and tap water were measured. The testing of two water types was performed to measure not only the temperature effects on the output but also the type of water used. To obtain temperatures below room temperature, the water was chilled in a refrigerator prior to the reading. Then to obtain temperatures greater than room temperature, water was placed in an oven set to 100 °C and measurements were recorded periodically as the water heated. With each Cementometer™ reading, the water temperatures were simultaneously measured using a Weber Instant-Read Thermometer probe with a +- 1 °C precision. Sample size and testing procedure were identical between the two water types and within each measurement. The results of the test can be seen in Figure 2.4.

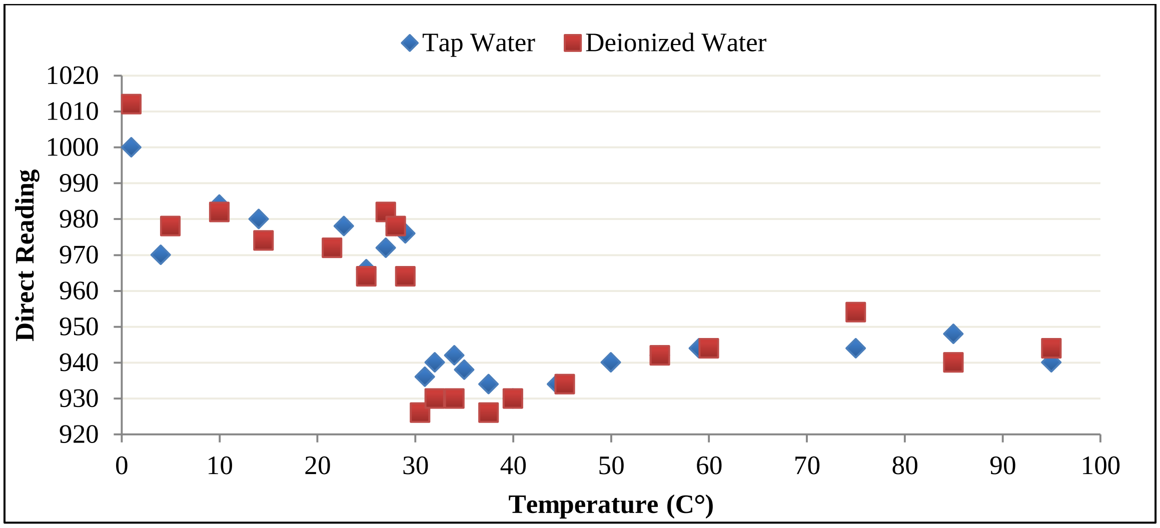

Figure 2.4 Direct reading values for liquid water measured at different temperatures.

As can be seen in Figure 2.4, there is no trend on the direct reading values over the entire temperature range of 1°C to 95°C. There is also no specific trend on whether deionized water or tap water increases or decreases the direct reading relative to each other. The data visually appears to have a sudden drop at 30 °C, although logic behind this temperature drop value is not known. For values more common in an outdoor concrete placement environment, it appears there may be a linear decreasing correlation between the direct readings of the water to an increase in temperature. With only a few data points, this trend is not yet confirmed. It is then concluded from this study care should be taken when using this meter at temperatures below 5°C and above 30°C as the output can be unpredictable outside this range. All laboratory measurements using the Cementometer™ and the previously shown frequency sweep analysis for dielectric properties were taken at room temperature (21°C +/- 2°C).

2.5 Cementometer™

The Cementometer™ is stated to rely upon an imposed microwave frequency and the measured dielectric constant of the material to estimate the quantity of free water in cementitious material (James Instruments 2010). The range of w/cm ratios the meter is capable of testing is reported to be from 0.35 to 0.65. The frequency cannot be adjusted within the Cementometer™ device and is not known. The Cementometer™ features a handheld console with a digital readout screen connected through a wire to two probes that are used to measure the dielectric of the mix. The internal software in the meter is hidden and cannot be accessed or modified.

Although the company does not specify the design details, it is assumed that one probe of the device transmits the microwave frequency while the second probe receives the returned wave signal, creating a capacitor system similar to that shown in Figure 2.2 but with rods instead of plates. Figure 2.5 shows the meter with its 5 inch long probes spaced 1 inch apart.

Internally, the device software stores the readings and has the option to generate an internal calibration for specific source materials used in the concrete. The same device then is presumed to predict the w/cm ratio based on either this internal calibration curve, or on an internal estimated w/cm calculation established on the difference in dielectric constant between water and other solids in the concrete.

a) b)


Figure 2.5 a) Cementometer™ probe device and handheld device; and b) probes with a ruler for scale.

2.5.1 Measurement Settings on the Cementometer™

On the handheld device, the user can select the desired mode for measurement. An image of the device's display during different modes and stages in selecting the mode are shown in Figure 2.6. The four modes are described as follows:

- **Direct Reading**: The direct reading is assumed to be the measured resistivity from the probes. The maximum direct reading was found to be 1300, which is measured when the meter is in air. The units of the direct reading are not known at this time.

- **User-Program**: This setting is used to calibrate the meter for different combinations of cementitious materials and solids. The meter can be calibrated for up to 9 different source material combinations, each calibration based on variation only in the water content of the mix. During each meter calibration for a given source material combination, a total of 45 measurements must be made to generate the internal calibration curve.

- **Type-I**: A pre-calibrated program from the manufacturer. The program is stated to be calibrated to a concrete mixture containing ASTM C150 (ASTM 2012b) Type-I cement as the sole type of cementitious material used in the mixture.

- **Type-III**: A pre-calibrated program from the manufacturer. The program is stated to be calibrated to a concrete mixture where an ASTM C150 (ASTM 2012b) Type-III cement is assumed to be the sole cementitious material used in the mixture.

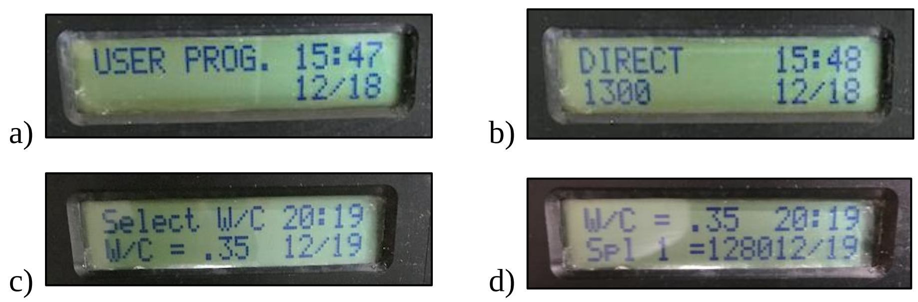

Figure 2.6 Handheld display screen indicating when user is in a) User-Program Mode, b) Direct Mode (in this case while holding device in air); or during User-Program calibration c) after selecting the calibration reading w/cm value, and d) the device then displaying the direct reading 1 out of 5 for that given w/cm value. The time stamp and date are shown on the top right and bottom right, respectively.

2.5.2 Water-to-Solid Content Measurement with Cementometer™

The direct output reading was found to be 1300 in air and can range from 940 to 1000 for tap water depending on the temperature of the sample (Section 2.4). While the units of this direct reading are unknown, it was expected that changing the amount of low-dielectric materials in the space between probes would produce a linear trend between the two extreme readings. To validate this hypothesis, blends of oven-dried sand and water at varying amounts were mixed and the Cementometer™ probe was used to measure the direct reading output. The results are shown in Figure 2.6 for natural sand and lightweight sand. It does appear that there is a linear correlation between water and sand alone, similar to that expected. This good correlation had a

R^2 value of 0.971 for the trial involving Beck Street sand and 0.962 for the fine Utelite sand (See Appendix A for sand properties).

The trend observed was different for the Beck Street sand than the Utelite lightweight fine aggregate. In the Beck Street sand experiment, the direct reading did not change significantly until after the sand reached a Saturated-Surface-Dry (SSD) state, indicating that the meter is not sensitive to the water inside the pores but actually sensitive to free water. However, in the Utelite fine aggregate measurements, the direct reading changed from the initial addition of water, including points below SSD condition, which indicated that the meter was sensitive to the water inside the pores of this lightweight aggregate as well as the free water. This contradiction may be attributed to the pore size and structure of the two sands. Further information on how the Cementometer™ may work with different aggregates is not studied at this time.

2.5.3 Source Materials Used in Study

One cement source, one fly ash source, four fine aggregate sources, and four coarse aggregate sources were investigated during this research study. All mixtures used an ASTM C150 (ASTM 2012b) Type II/V cement from Lafarge-Holcim's Devil's Slide Plant in Morgan, UT. The fly ash is an ASTM C618 (ASTM 2012c) class F from Headwaters Navajo Plant. The cementitious material chemistries and particle size information can be found in Appendix A. The mixture proportions and specific ranges of w/cm used for calibrating the Cementometer™ are summarized in Table 2.2. The "Point Project" mixtures were re-created at UDOT Central Materials Lab but using the collected aggregates from the same plant sites for the actual re-construction of I-15 interstate during the 2015-2016 year. Some of the aggregate sources changed during this time frame, so the date and location of the specific pit is shown in Table 2.2.

The Cementometer™ was also calibrated and tested to two Harper Precast mix designs: CSCC100GZ which is a standard self-consolidating concrete (SCC) mixture and C2400FBGZ which is for jersey barrier walls. "In-house" mixtures refer to those cast using the source materials at the University of Utah Concrete Lab. All aggregate properties can be found in

Appendix A. All aggregates used for calibrating and testing were carefully prepared to SSD condition since NDT James Company recommends this in order to insure the most accurate output from the device. ASTM C127 (ASTM 2012a) was followed for conditioning the fine aggregates.

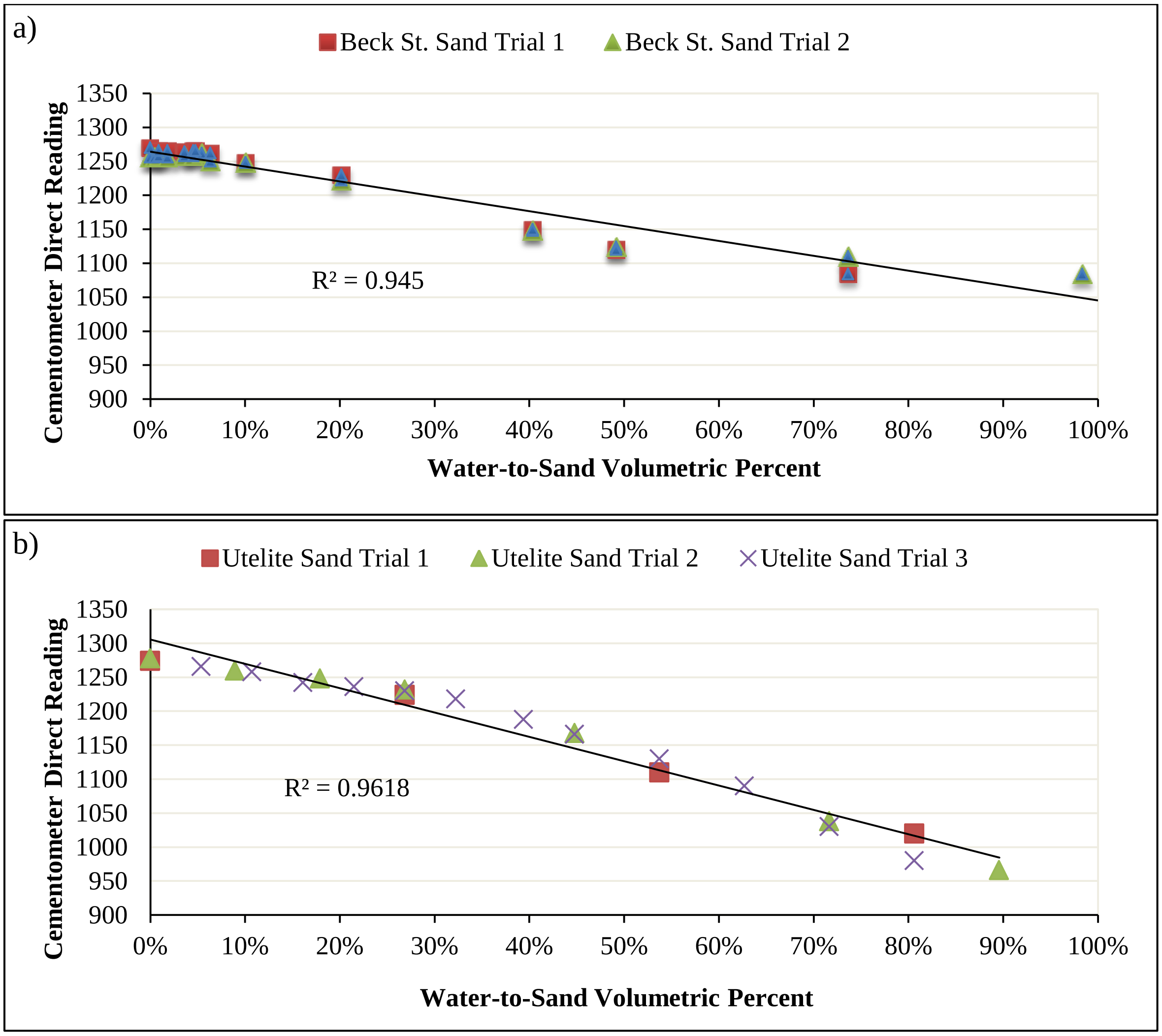

Figure 2.7 Correlation of the direct reading output from the Cementometer™ for varying water to sand amounts for a) Beck Street natural sand and b) Utelite lightweight fines.

2.6 Calibration Mixing Procedure

During calibration, the Cementometer™ manual describes a step by step process for preparing the aggregates, batching aggregates based on their density, and adding increments of water to each desired w/cm ratio until the full range is met. Aggregates are expected to be added at SSD condition, although one of the mortar mixtures created in this study was also batched at air-dry condition to estimate the sensitivity of the device based on the initial condition of the sand. Specifics of the manufacturer's calibration method are described below and are updated in more detail in Appendix B. The Cementometer™ was calibrated to a total of the 14 different mixtures over the course of this study, as listed in Table 2.2.

Table 2.2 Mixture Proportioning for Calibration

Mix	Fly Ash Amount (% cementitious)	Moisture Condition of Sand	Moisture Condition of Coarse Aggregate	Aggregate Source*	Range of dosed¥ w/cm ratios
In-House 'Paste 1'	0	-	-	Beck Street	0.35 to 0.75
In-House 'Paste 2'	0	-	-	Beck Street	0.30 to 0.39
In-House 'Mortar 1'	0	SSD	-	Beck Street	0.35 to 0.75
In-House 'Mortar 2'	0	Air Dry	-	Beck Street	0.25to 0.65
In-House 'Concrete 1'	0	SSD	SSD	Beck Street	0.30 to 0.65
In-House 'Concrete 2'	20	SSD	SSD	Beck Street	0.35 to 0.75
Harper SCC CSCC100GZ	30	SSD	SSD	Harper	0.35 to 0.75
Harper Barrier C2400FBGZ	30	SSD	SSD	Harper	0.35 to 0.75
The Point 6025E Oct 2015	25	SSD	SSD	Point East	0.35 to 0.75
The Point 6025W Oct 2015	25	SSD	SSD	Point West	0.35 to 0.75
The Point 6025E Nov 2015	25	SSD	SSD	Point East	0.29 to 0.57
The Point 6025W Nov 2015	25	SSD	SSD	Point West	0.35 to 0.60
The Point 7025E Apr 2016	25	SSD	SSD	Point East	0.35 to 0.75
The Point 7025W Apr 2016	25	SSD	SSD	Point West	0.35 to 0.75

*Aggregate properties can be found in Appendix A.

¥ dosed mass ratio does not include adjustment for aggregate moisture condition from what is stated in table.

2.6.1 Manufacturer Calibration Method

Due to the variable dielectric generated by different hydrating and absorbing materials in concrete, the manufacturer recommends calibrating the meter by using the same concrete mixtures with the actual aggregates and cementitious materials as the ones that will be used for future in-situ mixture measurements. This ensures that the meter's user-program generates the most accurate reading.

For each combination of source materials to be calibrated in the user-program, the manufacturer recommends reading 9 w/cm ratios, starting from a 0.35 w/cm ratio, and then adding a fixed amount of water to produce increasing w/cm ratios up to 0.75. The manufacturer recommends also calibrating a batch size of 1 cubic foot of concrete. To generate the actual w/cm ratios during calibration, the manufacturer recommends that the aggregates start at SSD condition to avoid errors in the w/cm estimation due to user's estimated aggregates absorption. Also, during this calibration process, for each w/cm ratio reached in the mixture, the user must manually type in that w/cm value into the handheld device (shown in Figure 2.6a). After each w/cm value is entered in the system, the display then shows the direct reading value corresponding to the measurement (shown in Figure 2.6d). Because the direct reading value is expected to be highly dependent on slight alignment, orientation, location of the probe within the concrete, or even the distribution of solids between the probes, the manufacturer requires 5 different measurements per each w/cm value during the calibration. The steps found in Appendix B outline the procedure followed to prepare and mix the sample for calibration.

2.6.2 Direct Reading Calibration Curves versus w/cm Mass Ratio

The direct reading values shown during each calibration mixture of Table 2.2 were recorded and are shown in Figure 2.8 through Figure 2.11 against the input w/cm ratio value. These figures demonstrate what the direct output reading values displayed during each calibration water addition step compared to the actual w/cm ratio for that calibration step.

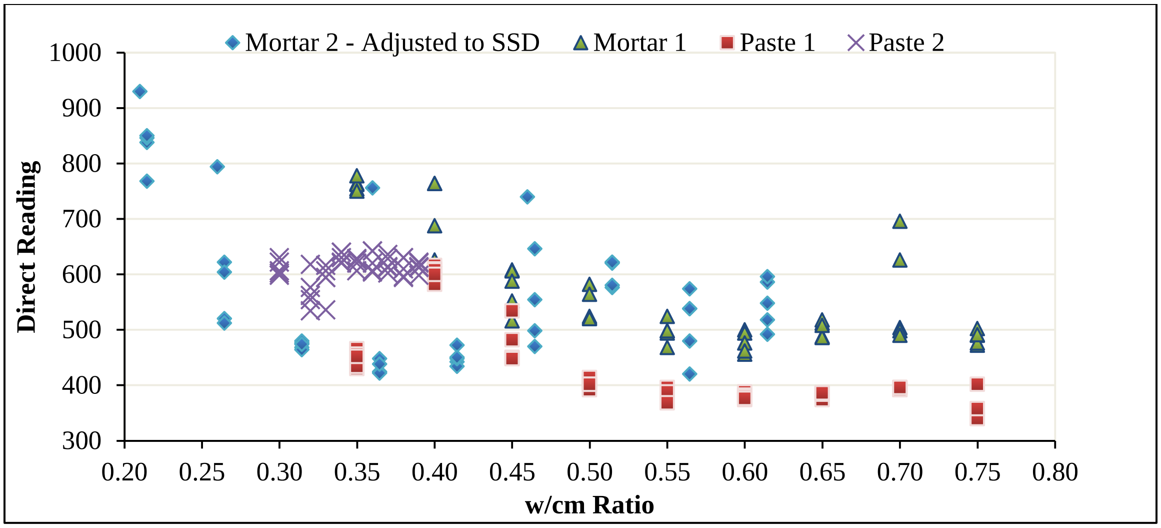

Figure 2.8 Direct readings during calibration of the in-house paste and mortar mixtures plotted against total water-to-cementitious mass ratio.

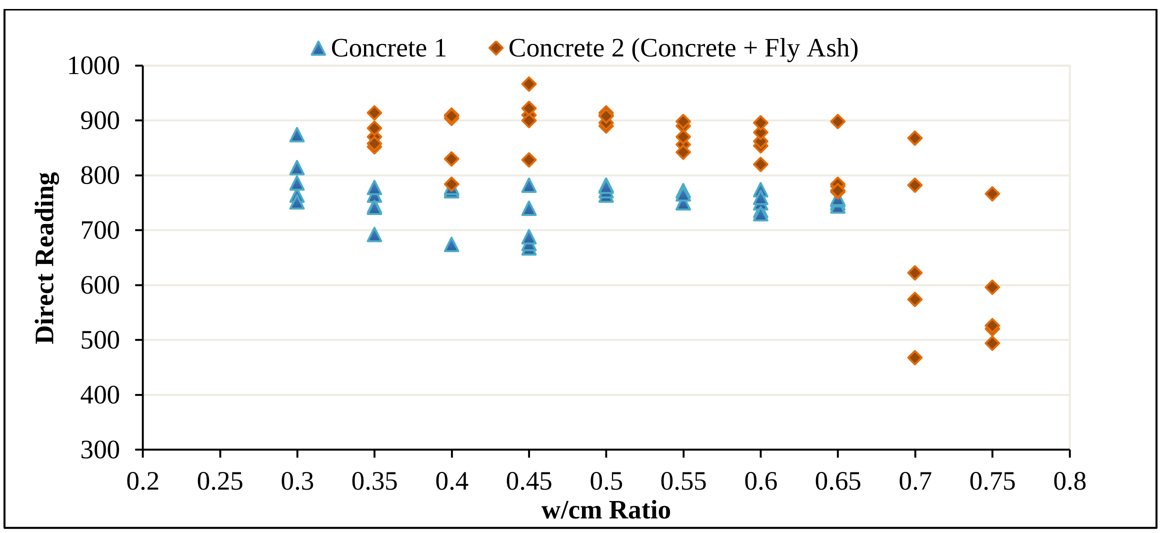

Figure 2.9 Direct readings during calibration of the in-house concrete mixtures plotted against total water-to-cementitious mass ratio.

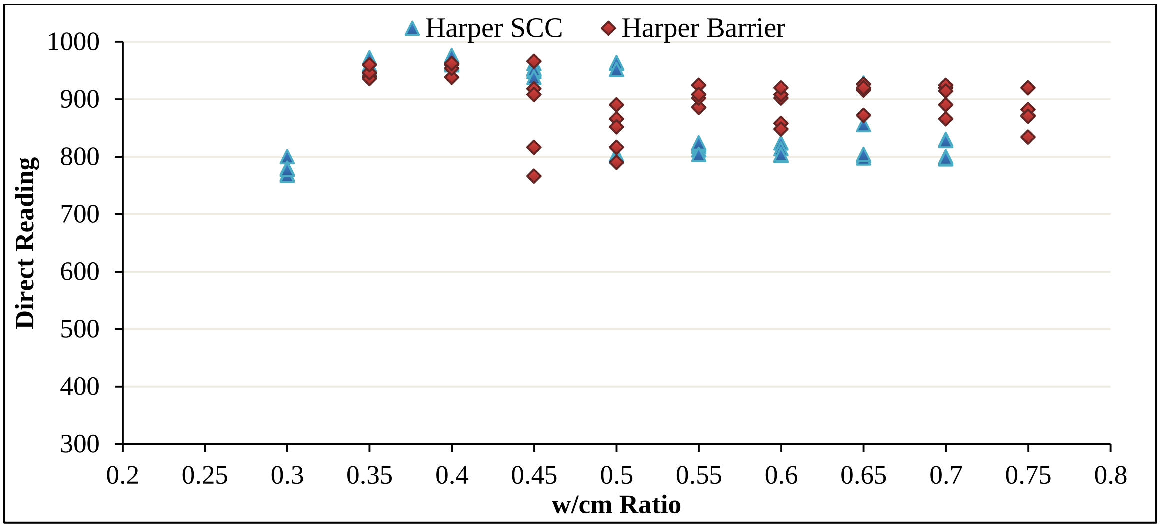

Figure 2.10 Direct readings during calibration of the Harper Precast mixtures plotted against total water-to-cementitious mass ratio.

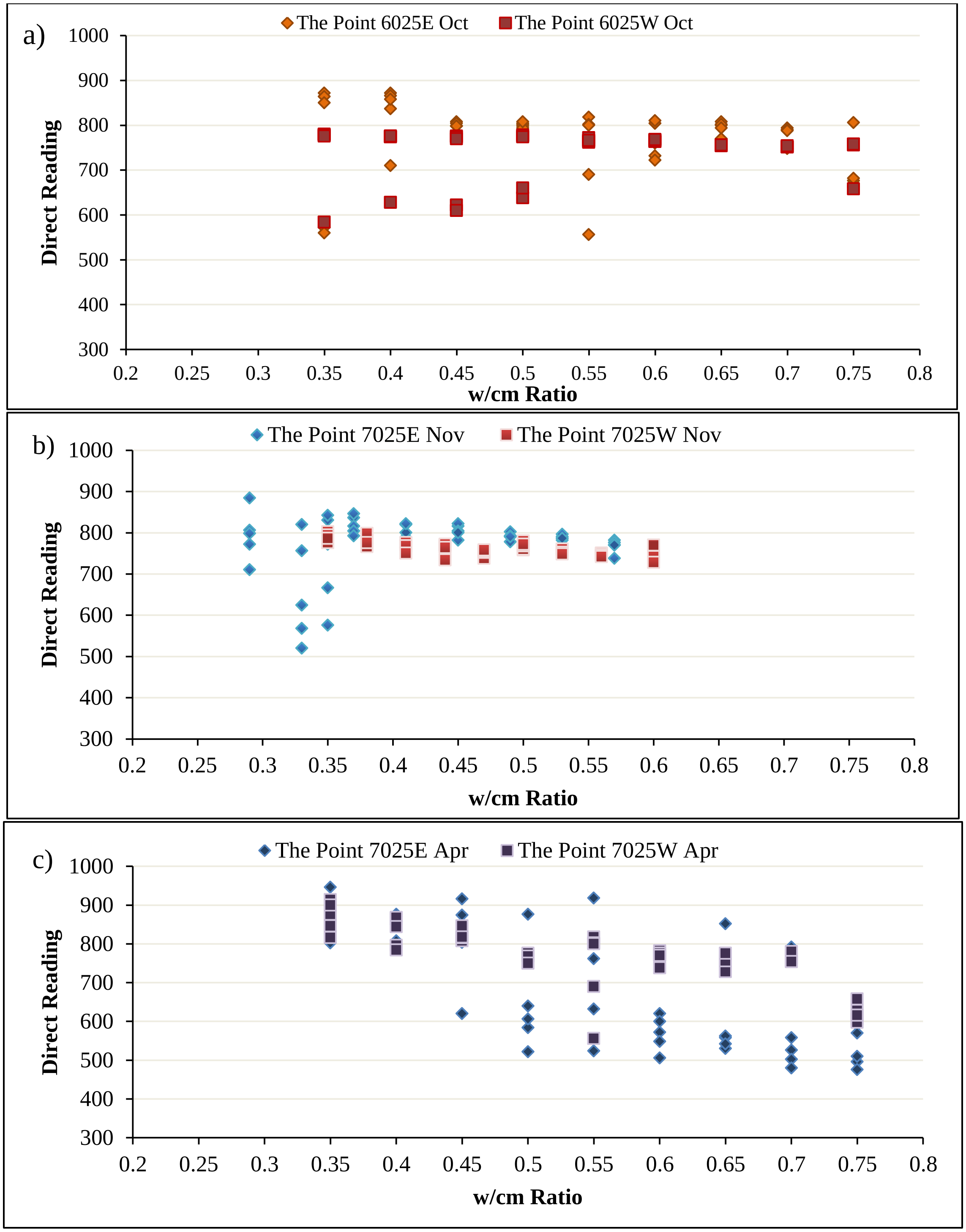

Figure 2.11 Direct readings during calibration of The Point mixtures measured in a) October 2015, b) November 2015, and c) April 2016 plotted against total water-to-cementitious mass ratio

2.6.3 Fine Aggregate Moisture Content During Calibration

Among the mortar mixtures, a batch was made with air-dry sand instead of SSD condition sand during calibration. The values input in the software during the mixture with air-dry sand were not the actual w/cm values. Instead, the input w/cm value was based on the total water amount added. Figure 2.12 shows the direct reading obtained from the mortar mixtures and investigating the effects of using the air-dry aggregates and the calculated actual w/cm ratio accounting for aggregate absorption (based on Appendix A and Appendix C), as well as the values for the same mortar mixture starting with SSD aggregates.

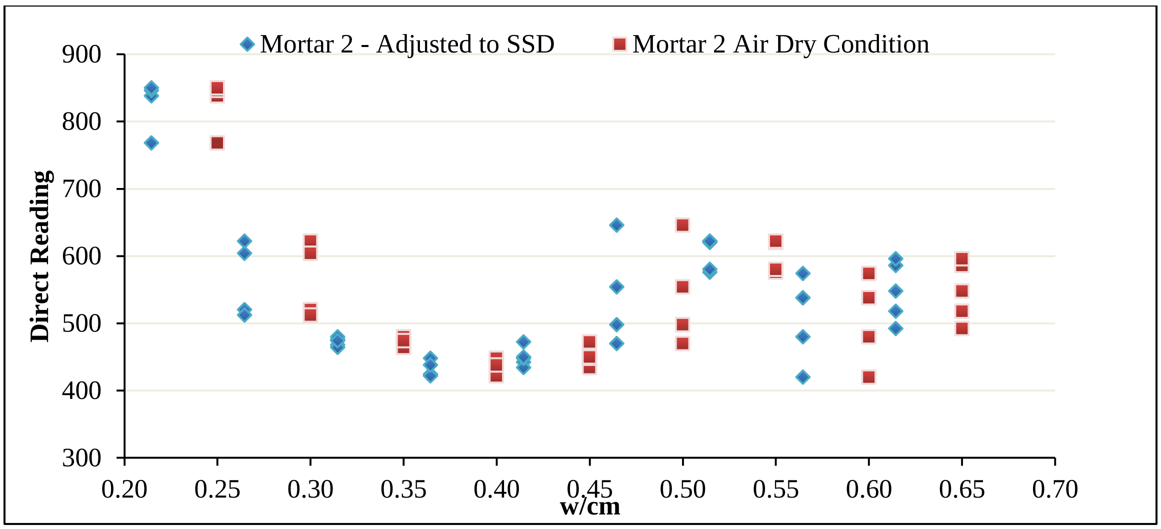

Figure 2.12 Direct readings during calibration for an in-house mortar mixture batched with the aggregates added at air-dry condition plotted against unadjusted water-to-cementitious mass ratio, compared to the same direct readings versus the adjusted SSD water-to-cementitious mass ratio.

The combined set of mortar mixtures, with the calculated actual w/cm ratio is shown previously in Figure 2.8. Even though both mortar mixtures are made from the same aggregate and cement sources, there does appear to be somewhat of a decreasing trend in direct reading values compared to increasing w/cm ratio. The scatter of the data is still visibly large, so it is expected to not be a precise measuring device for mortar.

2.6.4 Direct reading calibration curves versus water-solid volume ratio

Since fundamentally, the Lichtenecker mixing rule (Wu et al. 2003) indicates the effective permittivity is dependent on the volume of each material rather than mass (Equation 2), the same direct reading values for calibration are plotted against the calculated water to solids volume ratio, and are shown in Figure 2.13 through Figure 2.15. The volumetric ratio was calculated based on the procedure in Appendix C. The volumes of cementitious material and aggregates were calculated using the measured specific gravities and known masses used in the mix design (Appendix A and Table 2.2).

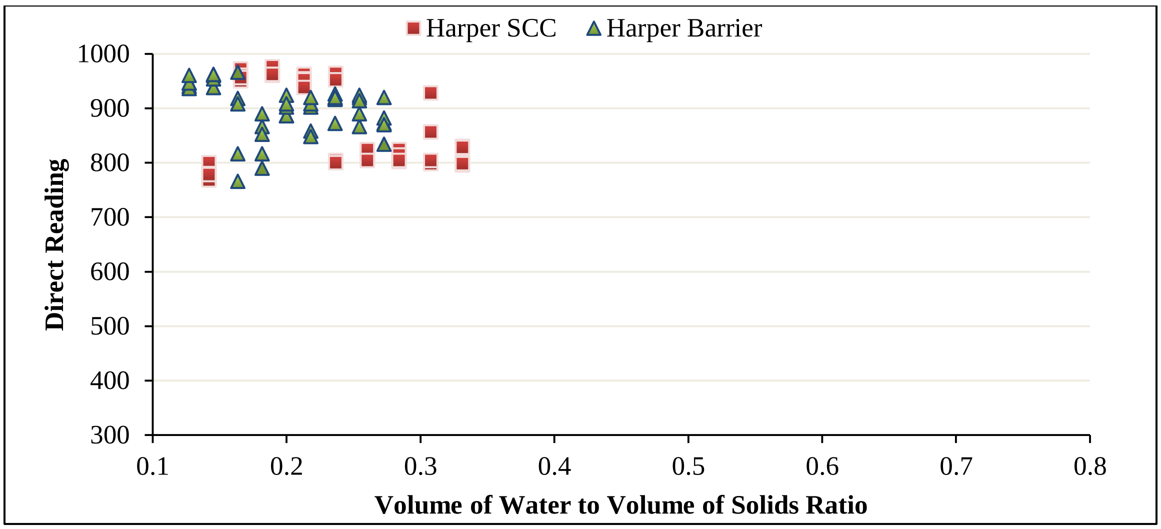

Figure 2.13 Direct readings during calibration of the Harper Precast mixtures plotted against volumetric ratio of water to solids.

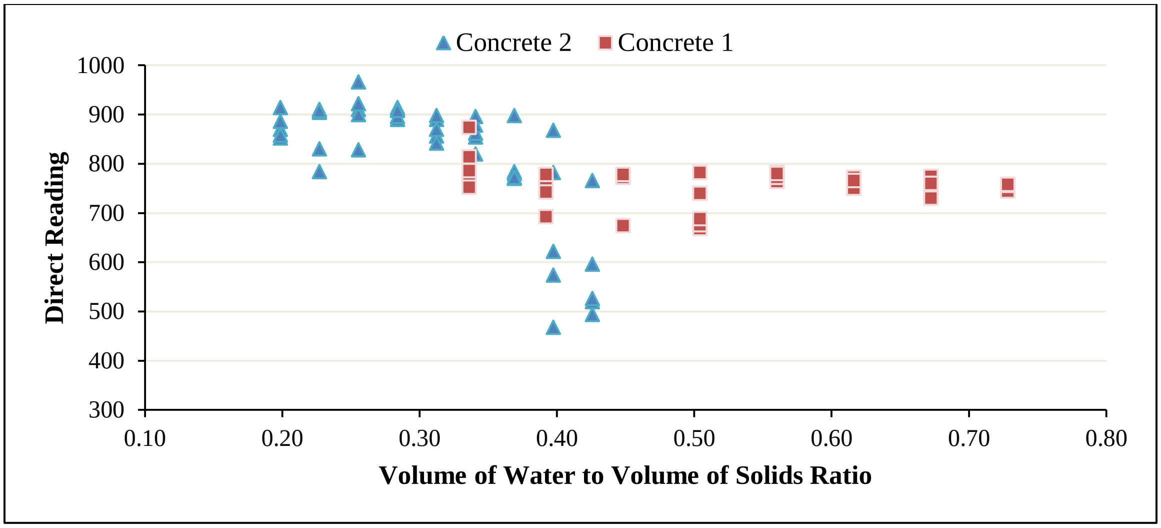

Figure 2.14 Direct readings during calibration of the in-house concrete mixtures plotted against volumetric ratio of water to solids.

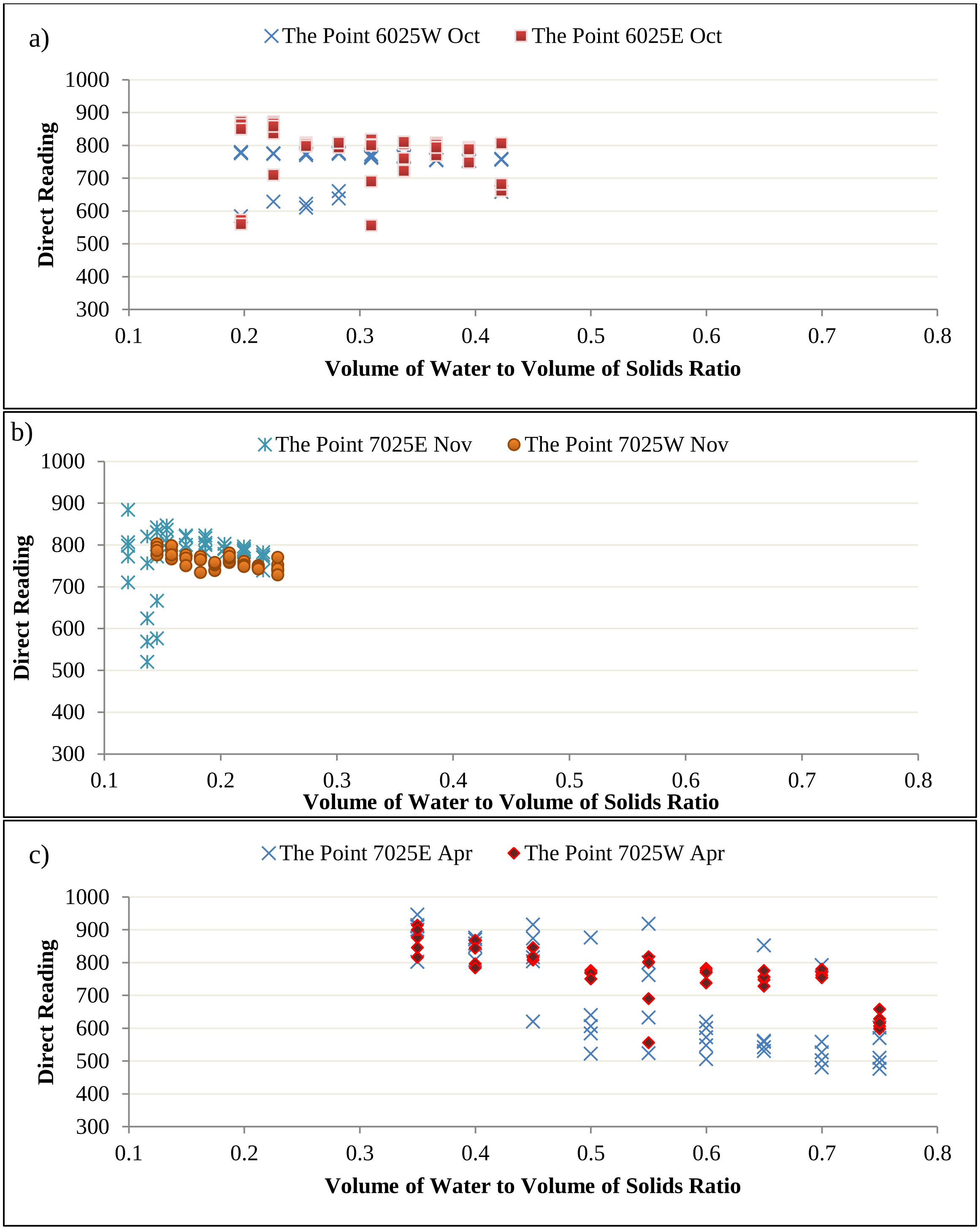

Figure 2.15 Direct readings during calibration of The Point mixtures taken in a) October 2015, b) November 2015, and c) April 2016 plotted against volumetric ratio of water to solids.

2.6.5 Summary of Calibration Curve Regression Analysis

NDT James Instruments, Inc. claims that the meter uses a straight line (linear) relationship to calibrate the actual w/cm mass ratio and the output of the device. To test the variability in the meter's calibration between the w/cm and direct reading, a regression equation of the actual w/cm mass values was plotted against the calibration direct reading values. The linear regression equations fit to the calibration direct reading values are shown in Table 2.3 along with each equation's R^2 values. A R^2 value of 1 indicates a perfect linear relationship and a 0 value indicates no linear relationship. Although the meter is assumed to use a linear relationship, the direct reading values obtained during the calibration demonstrate a poor linear correlation, as can be justified by the low R^2 values for all the calibrated mixes. The R^2 values for the w/cm mass ratio prediction of the device were all less than 0.57 indicating there are either likely outliers or high variability in the calibration readings. Even if a volumetric ratio of water to solids were used to derive the linear regression equation, this too produces a low R^2 value for all calibration mixtures.

2.6.6 Discussion on Calibration Challenges

The authors found it physically difficult to insert the probes in mixtures with w/cm ratios below 0.30 mainly due to the low workability of the mixture. When the w/cm ratios were higher than 0.55, all of the mixtures generated for calibration appeared to become segregated, where visibly it was noticed that coarse aggregates within a cement paste would sink to the bottom of the testing bucket.

The user also has the option to terminate the calibration process at any w/cm and thus generating the hypothesized calibration curve only up to the w/cm the calibration process was terminated at. However, when testing a program that was terminated before the 9 w/cm values were taken, the program was erroneous and was not able to read any value while testing.

Table 2.3 Calibration Linear Regression Equation and R^2 Values

Mix	Calibration Linear Regression Equation y= direct reading x=actual SSD w/cm mass ratio	R^2
In-House Paste 1	y = -394.93x + 642.19	0.48635
In-House Paste 2	y = 268.52x + 516.1	0.08982
In-House Mortar 1	y = -565.13x + 847.94	0.52268
In-House Mortar 2	y = -253.17x + 661.89	0.08367
In-House Concrete 1	y = -48.095x + 778.7	0.02189
In-house Concrete 2	y = -682x +1189.5	0.47987
Harper C2400FB-GZ	y =-107.2x + 958.47	0.08937
Harper CSCC100-GZ	y =-230.13x + 984.58	0.32487
The Point 6025E Oct	y = -123.53x + 839.97	0.04334
The Point 6025W Oct	y = 48.4x + 717.6	0.01484
The Point 7025E Nov	y = 143.26x + 713.9	0.03148
The Point 7025W Nov	y = -159.56x + 838.1	0.5298
The Point 7025E Apr	y = -922.53x +1196.9	0.5706
The Point 7025W Apr	y = -444.93x +1041.4	0.54988

Another issue noticed in the calibration process is that the Cementometer™ might record equal direct reading values for two different w/cm mixtures. For example, the direct reading recorded during calibration for w/cm ratios of 0.35 and 0.45 might be the same value, and thus when the user is later validating a mixture with a known w/cm of 0.35, the output w/cm might be either 0.35 or 0.45. The paste 2 calibration was tested in a narrow range of w/cm ratios in order to eliminate this repeated direct reading value issue. However, this still showed repeated direct reading values; and when the user calibration from paste 2 was later validated with a 0.4 w/cm ratio above the range calibrated, it still displayed a w/cm of 0.46 instead of displaying "out of range".

An issue with calibrating and taking 45 different readings is that when the user reaches the end of the calibration (on average, the calibration process takes 2 hours), the free water content of the mix may not necessarily reflect the free water that would be available if the mix was just initially batched. Although the start time of calibration was not investigated in this report, instead a quick study was performed as presented in section 4.1 to see if the measured

Cementometer^{TM} readings would produce a different value over the course of mixing time, similar to the situation encountered while calibrating.

3.0 VERIFICATION OF WATER-TO-CEMENT CONTENT

3.1 Validation Methodology

Once calibrated, various mixtures listed in Table 2.2 were re-batched at specific w/cm values to verify if the Cementometer™ would predict the same w/cm content as was actually batched. A total of 195 mixtures were tested for this validation, of which 157 are concrete mixtures with w/cm ratios varying from 0.30 to 0.55. The number of w/cm measurements for the three different mixture types (concrete, mortar or paste) in this validation can be seen in Figure 3.1.

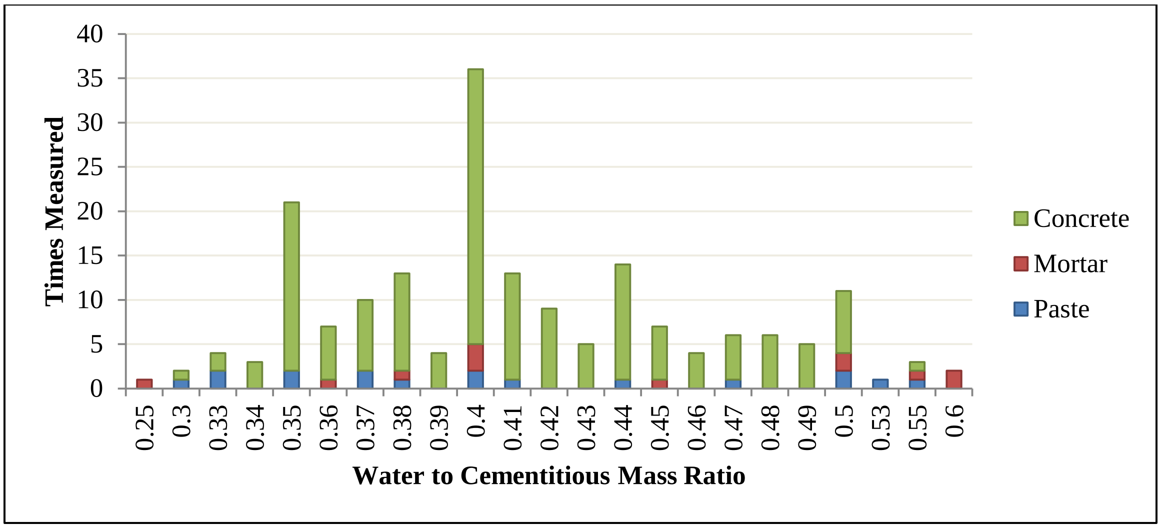

Figure 3.1 Frequency of validation measurements for each w/cm.

The same material sources and mix designs were used as the calibrated mixtures shown from Table 2.2. The actual w/cm was calculated based on batched weights created in the lab or at the plant before any additional water was added and based on the SSD condition of aggregate. Specimens were mixed for calibration and validation in the same environment and expected similar room temperature during measurement.

Once the mixtures were batched, a representative sample was placed in a bucket and the meter's probes were inserted in the mixture. The four possible mode outputs were then recorded. The bucket size and sample size varied in some mixtures. However, it must be noted that the sample size used for validation was identical to the one used for calibrating to ensure consistency of the procedure.

3.2 Validation Results

For each mixture in this validation, all four Cementometer™ modes were recorded. The user-program, Type I, and Type III modes produce anticipated water-to-cement contents as outputs, so these are plotted against actual water-to-cementitious content. The validation measurements for cement paste and mortar mixtures are plotted in Figure 3.2and Figure **3.3**, respectively. A value of "0" shown in the output y-axis of Figure 3.2 and Figure **3.3** was actually "out of range" displayed on the device.

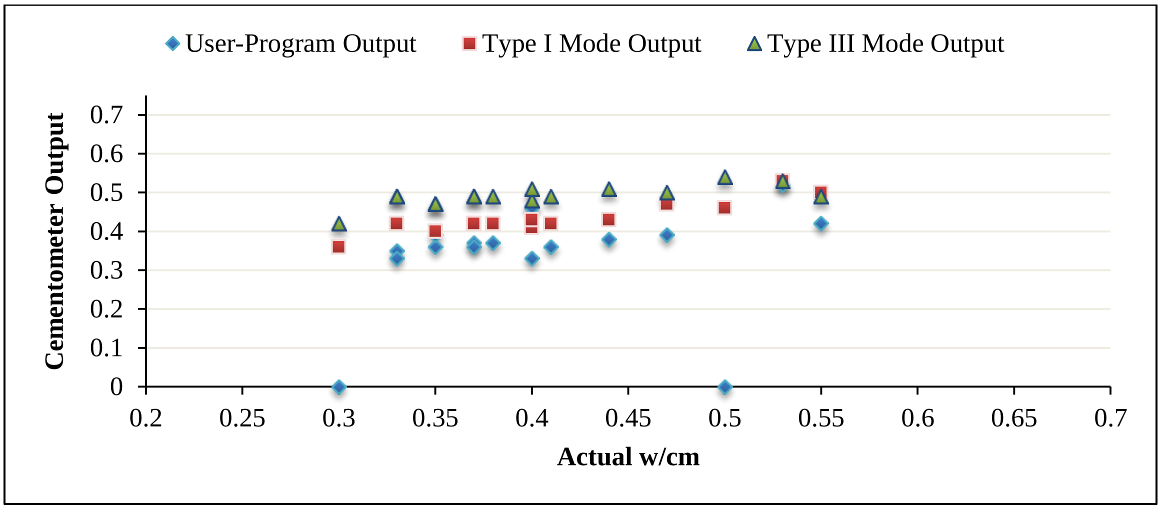

Figure 3.2 Actual water-to-cementitious mass ratio against Cementometer™ predicted w/cm values for the in-house cement paste mixtures. A zero value is actually "out of range" on Cementometer™.

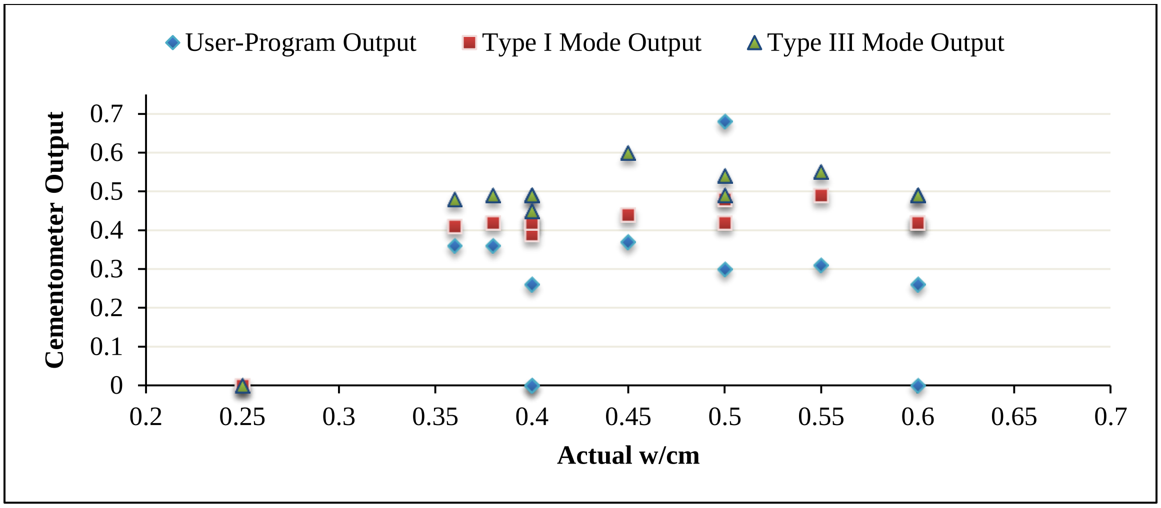

Figure 3.3 **Actual water-to-cementitious mass ratio against Cementometer™ predicted w/cm values for the in-house mortar mixtures. A zero value is actually "out of range" on Cementometer™.**

The validation measurements for all concrete mixtures are plotted in Figure 3.4. This figure with concrete mixtures does not include any of the "out of range" values in the plot, and the same "out of range" values were omitted from the statistical analysis mentioned later in Section 3.3. Of the 157 concrete mixtures tested, the user-program mode's read "out of range" 54 times or 34% of the readings. The Type I mode only read "out of range" 1 time and Type III never read "out of range". The line in the figure presents what a 1:1 correlation would be for the meter's predicted w/cm and the actual w/cm values.

As can be seen in Figure 3.2 through Figure 3.4, the meter rarely predicts the actual w/cm. Paste mixtures readings visually appear to be more linearly related to the w/cm, compared to the visual comparison with mortar and concrete mixtures. From the figures, the user-mode output visually appeared to have the highest deviation from the actual w/cm, followed by the Type I mode and then Type III. Visually, Type I mode appears to over predict when the actual w/cm is below 0.40 and under predict when the actual w/cm is above 0.40. Type III mode appears to over predict across most of the range. Sections 3.3.2 and 3.3.3 discuss the deviation and absolute difference that the expected w/cm values had for each mode.

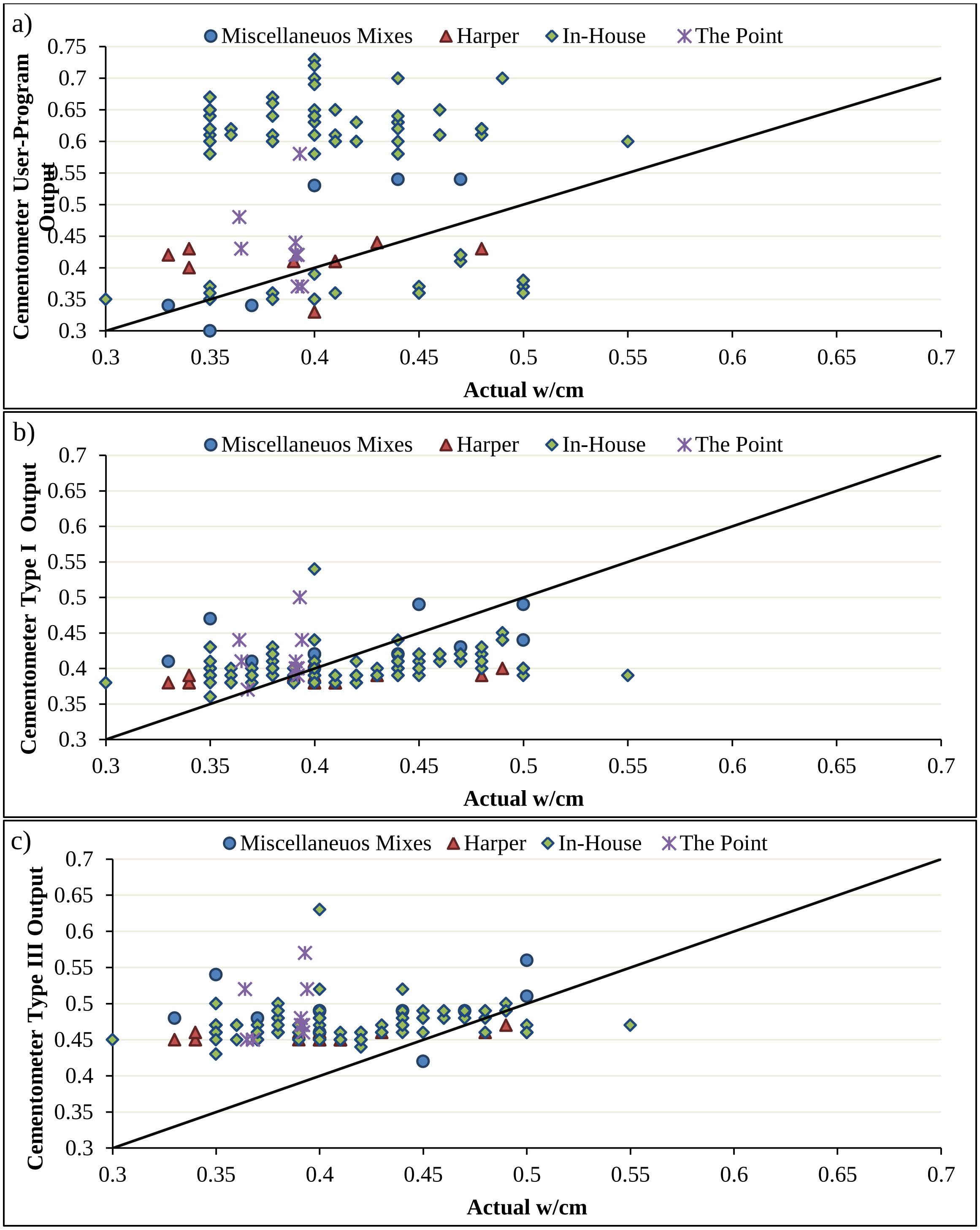

Figure 3.4 Actual water-to-cementitious mass ratio against Cementometer™ a)User-Program output b) Type I mode and c) Type III mode for all concrete validation mixtures. Any "out of range" readings are not shown here.

3.3 Statistical Analysis

To verify the precision and accuracy of the meter, six statistical analyses were performed. The analyses were done on the concrete test results only, and excluding any readings of "out of range". A regression analysis, standard deviation, and absolute difference were used to assess the precision of the Cementometer™ modes in order to determine whether the meter can differentiate between two similar water contents. Then a standard T-test analysis along with the sum of squared error were used to assess the accuracy of the three different modes (user-program, Type I and Type III) in terms of whether the Cementometer™ might present a w/cm value close to the actual w/cm. Finally, a confidence interval was calculated based on the T-test, which helps to present statistically the range of expected w/cm values that the Cementometer™ may give as an output for a given mixture's actual w/cm ratio.

3.3.1 Regression Analysis

A linear regression analysis was performed on the three different modes of the meter. This analysis tests the linearity between the actual w/cm and the output w/cm value from the meter. Unlike the regression analysis for calibration, this only looks at w/cm output values and is based only on the validation measurements, as were shown graphically in Figure 3.4. The R^2 value represents the amount that a variation in the actual w/cm ratio would affect the output of the meter. As summarized in , all three modes had a near zero R^2 value, indicating that there was little to no linear correlation between each of the Cementometer™ modes with respect to the actual w/cm. Table 3.1 also summarizes the mean and standard deviation values of the entire concrete validation set.

Table 3.1 Actual to Predicted W/C Ratio Statistics of Each Meter Mode

Mode	Linear Regression R^2	Mean x	Standard Deviation s	Sum of Square Error SSE
Actual	-	0.41	0.04	-
User-Program	0.0034	0.54	0.12	3.603
Type I	0.0652	0.40	0.02	0.3226
Type III	0.0291	0.47	0.02	0.8969

3.3.2 Standard Deviation

The mean and standard deviation for the output obtained from the three modes were calculated and the values are presented in Table 3.1. The standard deviation represents the average expected w/cm dispersion between the w/cm output value and the mean output value. As can be seen in Table 3.1 for the entire mode data set validation measurements, the standard deviation was 0.02 for both the Type I and Type III modes and a much higher standard deviation of 0.12 for the user-program mode. This actually reflects that the distribution of output values of these three modes do not seem to cover the full range of the actual w/cm ratios that the meter claims to quantify (0.35 to 0.65). It also reflects the high variability that the user-program mode has in predicting w/cm.

3.3.3 Absolute Difference and Sum of Square Error (SSE) for Each W/CM Ratio

The absolute and average difference between the actual w/cm and the output w/cm of the three modes was calculated and plotted in Figure 3.5. The SSE represents the expected error (squared difference) of the individual output w/cm values from the actual w/cm. The SSE values for the different w/cm measured are shown in Figure 3.6. The difference between the absolute difference and the SSE calculations is that the SSE sums up each individual measurement's error values. Summing the values gives a better representation of the variability of error since the error of the same w/cm from one reading to the other isn't necessarily equal. It must be noted that some measurements were excluded from the analysis because they read "out of range", and as such, some user-program measurements appeared to have a low average difference and low SSE from the reduced sample size. An example calculation of the SSE can be found in Appendix D.

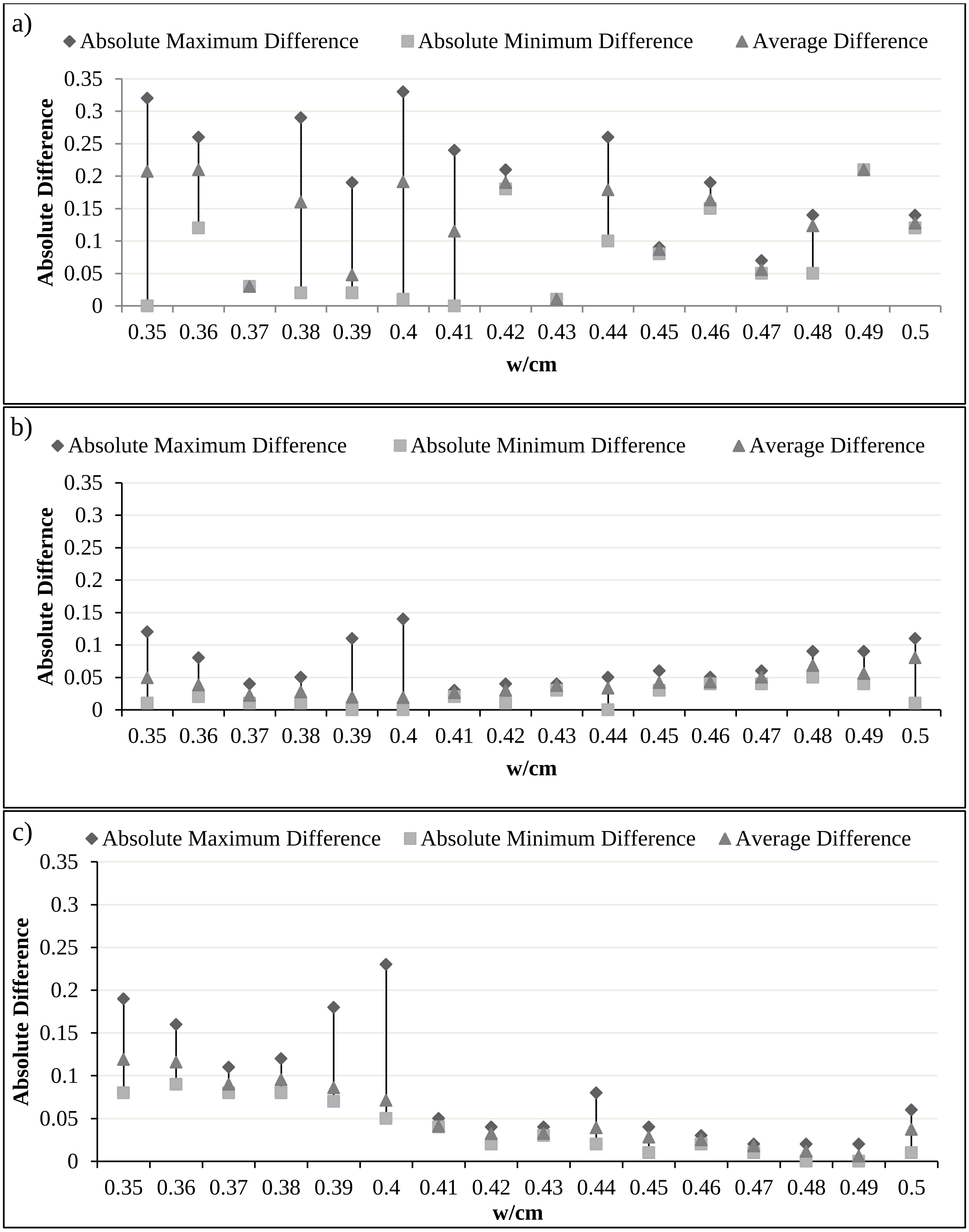

Figure 3.5 Absolute maximum, minimum, and average difference between actual w/cm and a) User-program b)Type I and c)Type III mode w/cm values.

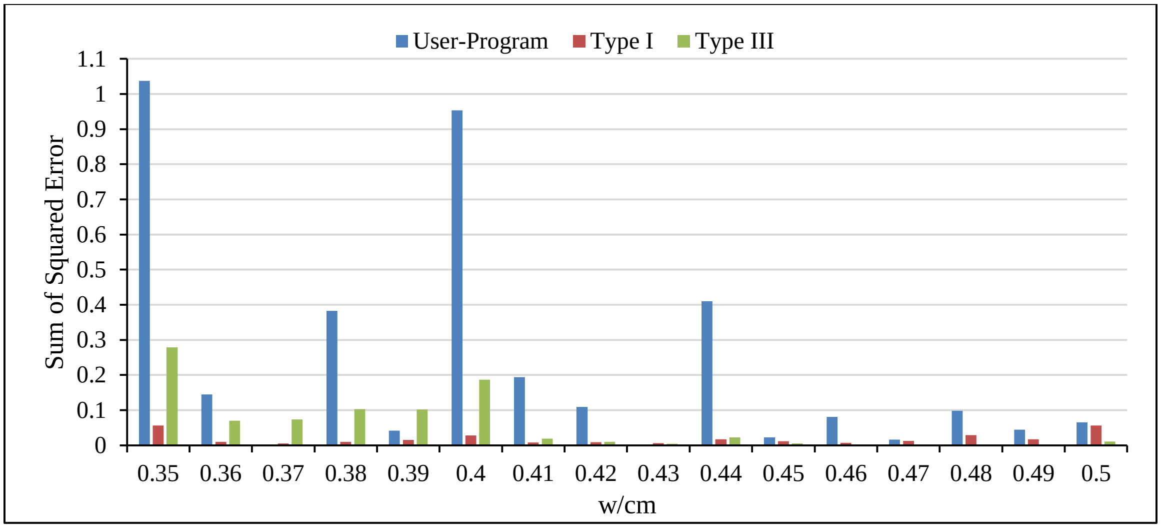

Figure 3.6 Sum of square error for the three different modes across concrete w/cm mixtures validated.

The user-program had the highest differences, particularly the highest average difference of 0.23 and highest SSE at an actual w/cm of 0.35. The user-program had the highest difference and SSE across most w/cm when compared to Type I and Type III programs. The smallest average difference for Type I mode was 0.02, seen at w/cm mixtures of 0.37, 0.39 and 0.40. For the Type III mode, the smallest average difference was 0.01 at w/cm mixtures of 0.48 and 0.49. In general, Type I and Type III modes had SSE values below 0.05 for most w/cm mixtures. The absolute difference does not indicate whether the meter over or under predicts, such as was seen visibly in Figure 3.4 or from the mean in Table 3.1 . This absolute difference and the SSE do give an idea of the precision of the device relative to the actual w/cm content.

The absolute difference and SSE analysis may suggest that the meter's Type I and Type III may be preferred due to the lower variability. However, the previously identified R^2 value indicated these modes cannot differentiate small changes in w/cm content and further analysis on the accuracy is presented in the next section.

3.3.4 Sample T-Test for Accuracy

A standard t-test will be used to compare accuracy of each of the Cementometer^{TM} modes in predicting actual w/cm content. Two separate t-tests were performed: one t-test was performed comparing the difference between output w/cm and actual w/cm for each mode; a second set of t-test calculation was performed comparing output values for each separate individual actual w/cm ratio mixture.

Since the w/cm ratio changes, the first t-test performed only compares how far off the Cementometer^{TM} output may be for all mixtures based on the calculated difference from the actual w/cm to the output w/cm. Only the modes which produce w/cm values (i.e., User-program, Type I, and Type III) were used for this first t-test.

For this t-test, the null hypothesis is that the entire mode's mean difference is zero. The alternate hypothesis is that the samples' mean difference is not zero. This calls for a two-sample t-test to be performed. An example calculation of the t-test can be found in Appendix D. A 95% level of confidence was selected and thus a p-value of less than 0.05 means the null hypothesis can be rejected with 95% confidence. Table 3.2 presents the findings from comparing the differences between the output w/cm and the actual w/cm for each mode. Since the p-values are significantly low for all three modes, it can be concluded that the hypothesis is rejected, and thus the readings for these modes are not equal to the actual w/cm.

Table 3.2 T-Test Parameters for Entire Mode Data Set of Concrete Mixtures

Mode	Sample size	Mean Difference	Standard Error	T-value	p-value	Hypothesis x = 0
User-Mode	108	0.12347	0.0861	11.47	0.000	Reject
Type I	156	-0.00813	0.0356	2.02	0.044	Reject
Type III	157	0.05943	0.0356	14.80	0.000	Reject

The Type I mode does have a slightly higher p-value compared to the other modes, yet for a level of significance of 0.05 the hypothesis is rejected. With the previous precision analyses performed, it can be also be suggested that this Type I mode, along with the other modes, have a high variability, which can indicate a possible "type-1 error". A statistical t-test "type-1 error" is interpreted that the Cementometer™ Type I mode may appear to give an accurate reading, yet in fact it may not be the true value.

A two tailed sample t-test was also performed on individual w/cm mixtures in order to statistically assess the accuracy of the meter for a given w/cm made. The null hypothesis for this second t-test set is that the mean of the meter's output (calculated only for mixtures cast with the same w/cm) is equal to the actual w/cm. The alternative hypothesis is that the mean of the meter's output is different than the actual w/cm. Table 3.3 summarizes the p-values obtained from the second t-test analysis for each actual w/cm mixture. Again for a 95% confidence, this means any p-value less than 0.05 indicates a rejected hypothesis, or that the mode cannot predict an equivalent w/cm value. While some of the p-values cannot be rejected, again the high variability of these small w/cm ratio sub-sets may cause a "type-1 error" or incorrectly predicting a false positive.

Table 3.3 P-Values for the Validation Measurement W/CM Ratios

w/cm	User-Program	Type I	Type III
0.35	0.000	0.000	0.000
0.36	0.043	0.027	0.001
0.37	*	0.000	0.000
0.38	0.013	0.000	0.000
0.39	0.154	0.132	0.000
0.40	0.000	0.727	0.000
0.41	0.054	0.000	0.000
0.42	0.003	0.000	0.000
0.43	*	0.001	0.001
0.44	0.000	0.000	0.000
0.45	0.001	0.108	0.140
0.46	0.007	0.000	0.003
0.47	0.318	0.000	0.001
0.48	0.019	0.000	0.793
0.49	*	0.003	0.704
0.50	0.000	0.004	0.285

*****Output contained only "out of range" readings.

3.3.5 Confidence Interval

The confidence interval was calculated to represent the range of w/cm values that the Cementometer^{TM} may give with a 95% probability (0.05 level of significance). This is calculated based on the individual w/cm ratio t-test values from 3.3.4. The confidence interval for each mode is shown in Figure 3.7.

Among the three modes, the confidence interval range for the user-program has a wide range up to a 0.388 difference in w/cm values occurring for mixtures at a 0.36 actual w/cm content. Type I and III both visibly demonstrate a more narrow range of possible w/cm values for any given mixture. The confidence interval range width for any given w/cm mixture measured with the Type I mode can vary across 0.08 w/cm values and with a Type III varies up to 0.07 w/cm values.

Very few of the measurements actually show a range that lies across the actual w/cm of the mixture. With Type I, the only w/cm ratios that overlap the actual w/cm content with 95% confidence are 0.39, 0.40 and 0.45. With Type III, the overlap with actual w/cm contents are 0.45, 0.48, 0.49 and 0.50. Those w/cm contents are also the only ones from the range tested that have a p-value equal to or greater than 0.05. Although the confidence interval and p-value analysis suggests that the meter can be used at these w/cm mixtures, the analysis of the absolute difference shows that the risk is still high when using the meter's modes at these w/cm values.

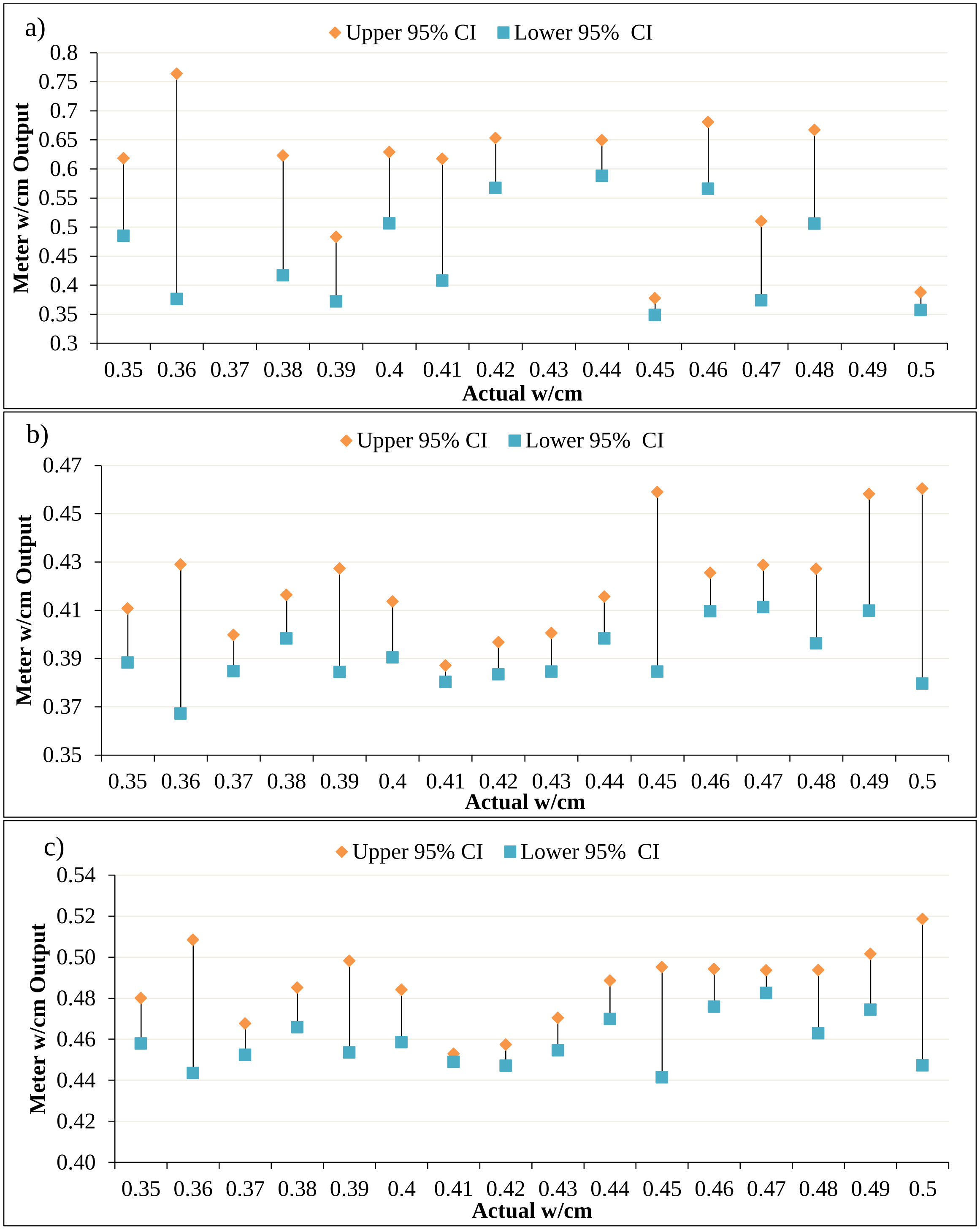

Figure 3.7 Range of expected output w/cm values with 95% confidence for modes a) User-Program, b) Type I mode, and c) Type III mode.

3.4 Discussion on Statistical Findings

Among the three modes of the Cementometer™, all demonstrated high variability. The Type I mode appears to produce w/cm values on average around 0.40, and with a 95% confidence that the Type I mode may display something between 0.37 and 0.46 regardless of the mixture that was created. Type I may appear to be accurate because these w/cm values it displays are common to mixtures created. However, due to the low R^2 values and low p-values, it is proven that the Type I, Type III, and User-Program modes cannot distinguish between two mixtures of similar w/cm content and are in fact not accurate at predicting actual w/cm values.

4.0 ADDITIONAL OBSERVATIONS

4.1 Effects of Mixing Time

As mentioned earlier in this report, concrete electrochemical properties depend on the hydration phase and time. It is hypothesized that the meter may be sensitive to ionic concentration in the pore solution or the water availability before being bound up into hydration products. The authors anticipate that the Cementometer^{TM} should be used just after mixing and prior to hardening stages of hydration. At this time, a brief study was done to investigate the effect of longer mixing times (possibly due to longer transportation times or to re-mixing on site).

To test the time effect on the output of the meter, mixtures of four different w/cm contents (0.35, 0.38, 0.40, and 0.44) were tested after different mixing times. Each mixture was tested at 15 minute intervals up to 60 minutes. The results are shown in Figure 4.1 for the direct reading values and Type I mode values. As can be seen in the figure, the direct reading values appear to slightly increase over time. However, the variability is still high in all measurements, and thus a one-way Analysis of Variance (ANOVA) was performed with a 95% level of confidence to analyze the difference (if it exists statistically) with the variable being the mixing time. The analysis was performed only on the two w/cm contents (0.35 and 0.40) that had 3 replicate measurements at each time; the other w/cm contents tested only had one measurement at each mixing time. When calculating the p-value shown in Table 4.1 for the direct reading and user-program, unequal variances were assumed. Because the ANOVA produced an error when using the same unequal variance assumption for Type I and Type III modes, instead the p-values displayed in Table 4.1 are for an equal variance assumption.

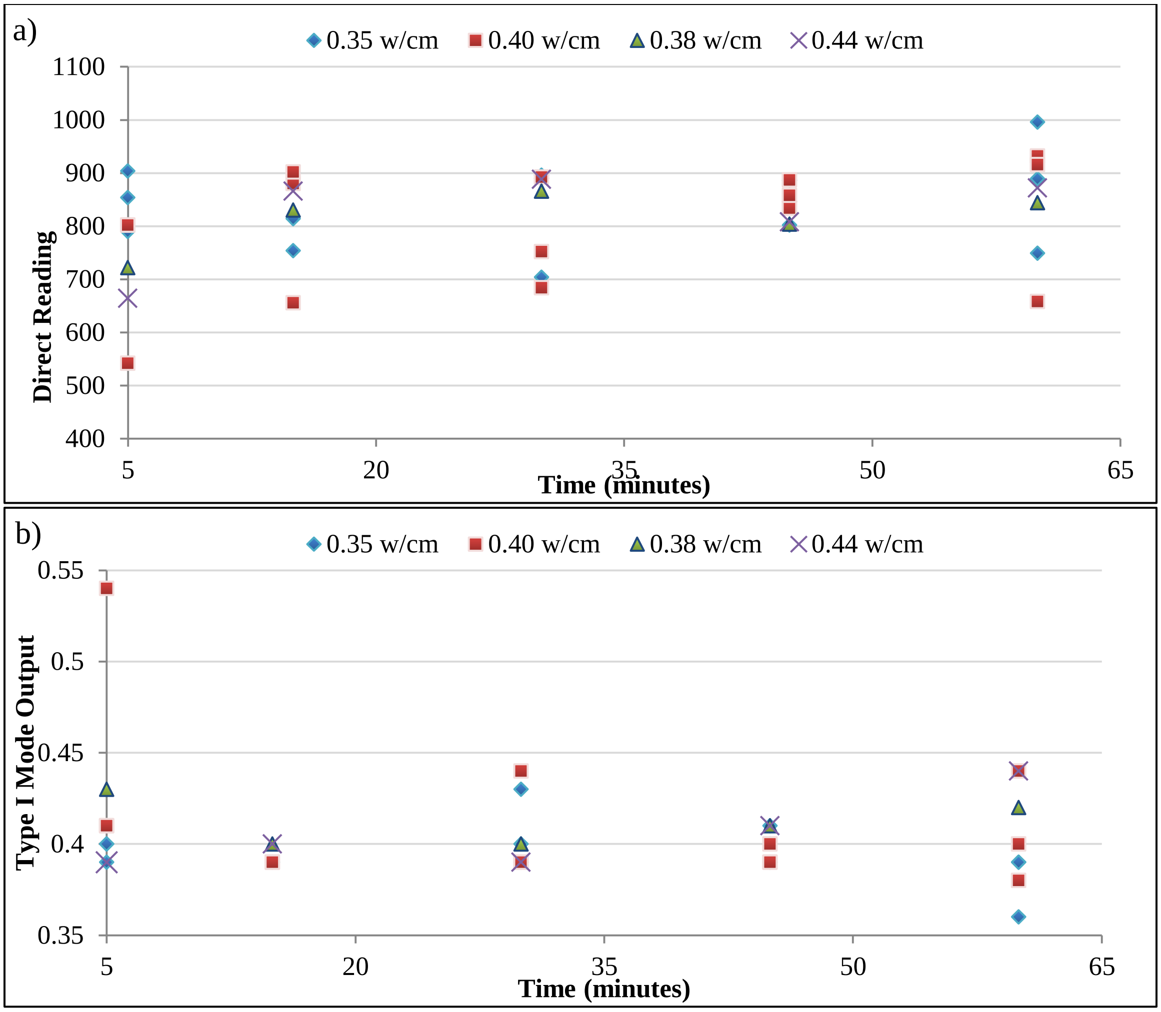

Figure 4.1 Cementometer™ output values shown for in-house concrete mixture of varying w/cm ratios recorded at different mixing times. a) Direct reading values and b) Type 1 mode predicted w/cm values.

Table 4.1 P-values from ANOVA Based on Influence of Mixing Time

w/cm	Direct Reading	User-program	Type I	Type III
0.35	0.979	0.286	0.208	0.681
0.40	0.594	0.924	0.334	0.344

The p-value of most importance in this analysis is the direct reading p-value since this mode does not depend on any conditions such as calibrated cement and aggregate content. It is then concluded from the ANOVA analysis that with 95% confidence, the hypothesis cannot be rejected. The variability was not assessed at this time, so it may be possible to still hypothesize that there is no difference between the mode outputs of the meter over a mixing time of 60 minutes for w/cm ratios of 0.35 and 0.40.

4.2 AASHTO T 318-02 Concrete Microwave Test Validation

As mentioned in the introduction, one of the common methods currently used by the industry for quality assurance of water content is the AASHTO T 318-02 microwave test. This moisture content microwave test was performed as an additional study to compare simultaneously with the Cementometer^{TM} recorded mode output values in the prediction of actual w/cm contents. Samples from five separate w/cm mixtures were created in addition to the previous validation tests and placed in a microwave to be tested with the AASHTO test. The "calculated w/cm ratio" of these five mixtures was based on the mixture proportions, the measured unit weight of the concrete, and knowledge of material properties. An example of the calculated w/cm ratio is described in Appendix C.

Figure 4.2 shows the moisture content values of the AASHTO microwave method along with the actual and calculated w/cm of each mixture. A linear trendline through the actual w/cm contents for this AASHTO method's moisture content has a R^2 of 0.62. Even with a small dataset of five measurements, the higher R^2 validates that the microwave method is significantly more precise than all the modes of the Cementometer^{TM}.

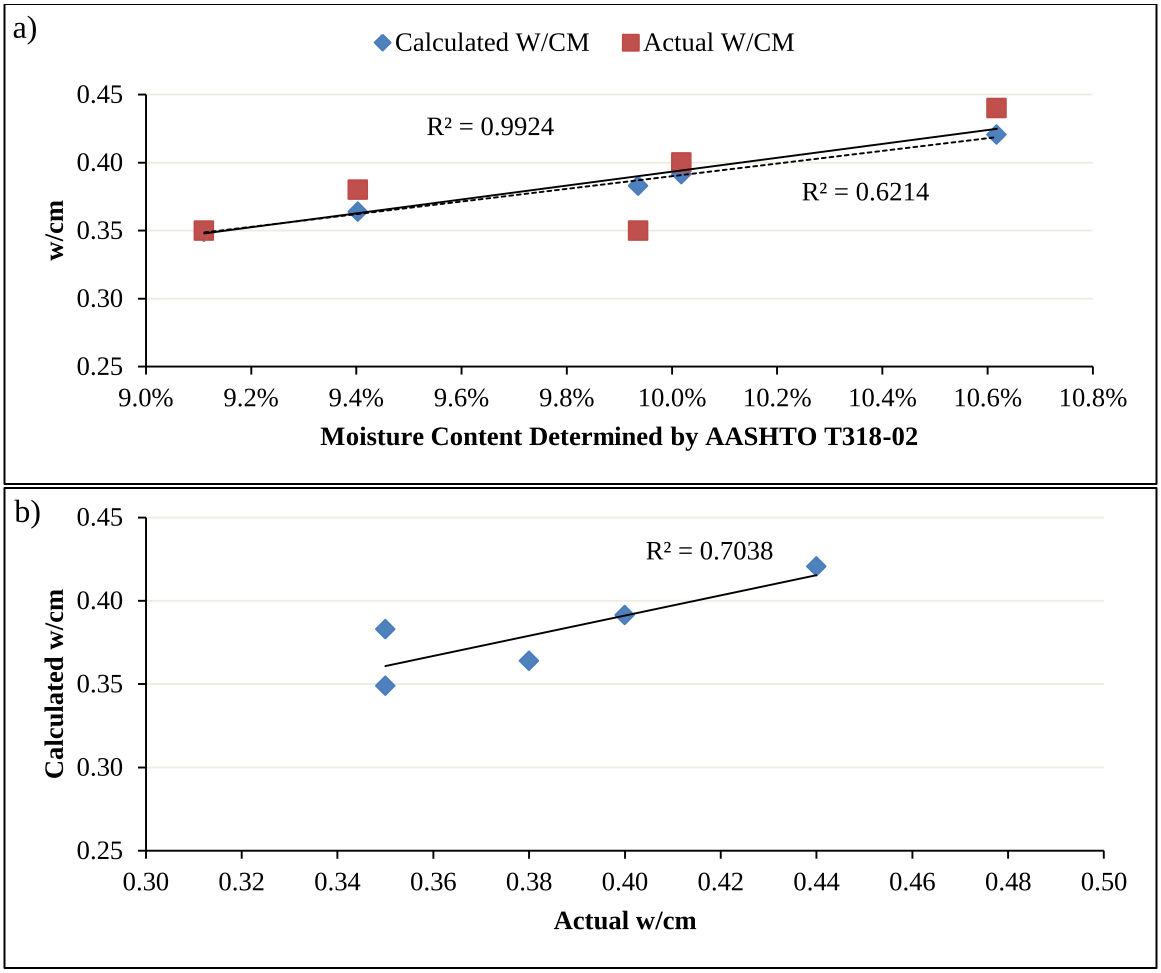

Figure 4.2 AASHTO T 318-02 Microwave Test results of a) moisture content against actual or calculated w/cm ratio and b) actual versus calculated w/cm ratio.

From Figure 4.2, the linear regression between the actual and this calculated w/cm value is a little higher in R^2 of 0.70. To verify how accurate the results of this AASHTO microwave test are, a t-test and SSE analysis were also performed between the actual w/cm and calculated w/cm. The hypothesis tested is that the mean difference of the actual w/cm and calculated w/cm is equal to zero. As can be seen in Table 4.2, the p-value obtained for this AASHTO method is much higher than what was calculated for each of the Cementometer™ modes. Due to the higher R^2 value, low SSE, and the failure to reject the null hypothesis, this AASHTO method is significantly preferred over the Cementometer™ device for predicting the actual w/cm content of a mixture.

Table 4.2 Statistic Comparison for AASHTO Microwave Test to Actual W/CM

Data	Sample size n	Mean Difference x	Standard Deviation s	T-value	p-value	Hypothesis x = 0	SSE
Actual w/cm	5	0.0025	0.0378	0.122	0.909	Do not reject	0.0018
Calculated w/cm	5		0.0273				

As an additional reminder to the users of these methods, this AASHTO method can be used to estimate w/cm content from the moisture content. However, to have an accurate estimate on w/cm, the user would need to know the aggregate properties such as absorption capacity and specific gravity, as well as yield and mass ratios of the concrete mix. See Appendix C for a sample calculation of the w/cm based on the moisture content obtained from the AASHTO microwave method.

5.0 CONCLUSIONS AND RECOMMENDATIONS

The Cementometer™ produces high variability in the predicted w/cm output regardless of the mode selected or the actual w/cm content. Among the modes, Type I and Type III modes have better precision (standard deviation of 0.02 across all w/cm contents) than the User-Program (standard deviation of 0.14) mode. Of the 157 mixtures tested ranging from 0.35 to 0.55 w/cm content for validating the meter, a t-test indicated that all three modes did not produce accurate w/cm values equivalent to the actual mixture. While Type I and Type III modes produces expected w/cm values at certain actual w/cm contents, the high variability shown in the absolute difference and the low R^2 value with a very low p-value less than 0.044 indicate this is not a good predictor of actual water content either. The meter is not recommended to be used as a quality assurance method for concrete or mortar as it is not precise or accurate enough to differentiate between two similar w/cm contents.

Further insights revealed that the direct reading outputs shown during calibration do not have any linear correlation with the batched w/cm contents (all R^2 values of paste, mortar, or concrete mixtures during calibration were less than 0.6). The direct reading is however linearly correlated (R^2 of 0.94 to 0.96) with the water content if the meter is used to test the moisture content of sand only, without the addition of cementitious materials.

Since the direct reading values were also found to be dependent on the temperature of the water, it is suggested that if the user chooses to calibrate their own mixture that the same temperature as would be expected on the day(s) of testing be used for the mix water.

The most precise method found in this study was using the existing AASHTO T 318-02 microwave test. The measurements performed for this study found a R^2 value of 0.62 and a confirmed high p-value of 0.91 between a calculated w/cm ratio from the method's moisture content against the actual w/cm ratio. While the Cementometer™ does produce a reading within a few seconds and is displayed as a w/cm value, the AASHTO test can still be measured within a 15 minute timeframe as long as a microwave oven is available. Additional calculations, as is shown in the Appendix C of this report, would be needed to verify the water content of the mixture using the AASHTO T318-02 method. It is recommended to use the AASHTO T 318-02 microwave oven method instead of the Cementometer^{TM} microwave probe method as a fast, precise, and accurate determination of the w/cm ratio.

6.0 PROPOSED FUTURE WORK

It is still theorized that a microwave probe device could be used to measure an accurate in-situ water content of a mixture. Therefore it is suggested that the settings and manufacturing of the existing device be further investigated or that a new device be made with controlled and known frequency, as well as including a possible software illustrating calculations, units of the measured outputs, and the calibration curve fit by the device. Ideally the calibration calculations could also be adjusted to include temperature, mix proportions, and chemical hydration effects on the output measurements.

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APPENDIX A. AGGREGATE AND CEMENT PROPERTIES

A.1 Aggregate Properties

In-House

Aggregate Properties	NMAS	Bulk Specific Gravity SSD	Absorption Capacity
Beck Street Pea Gravel	0.5"	2.67	0.28
Beck Street Limestone Aggregate	0.75"	2.62	0.43
Beck Street Sand	#4	2.57	1.90
Utelite Structural Fines*	#8	1.559	1.22

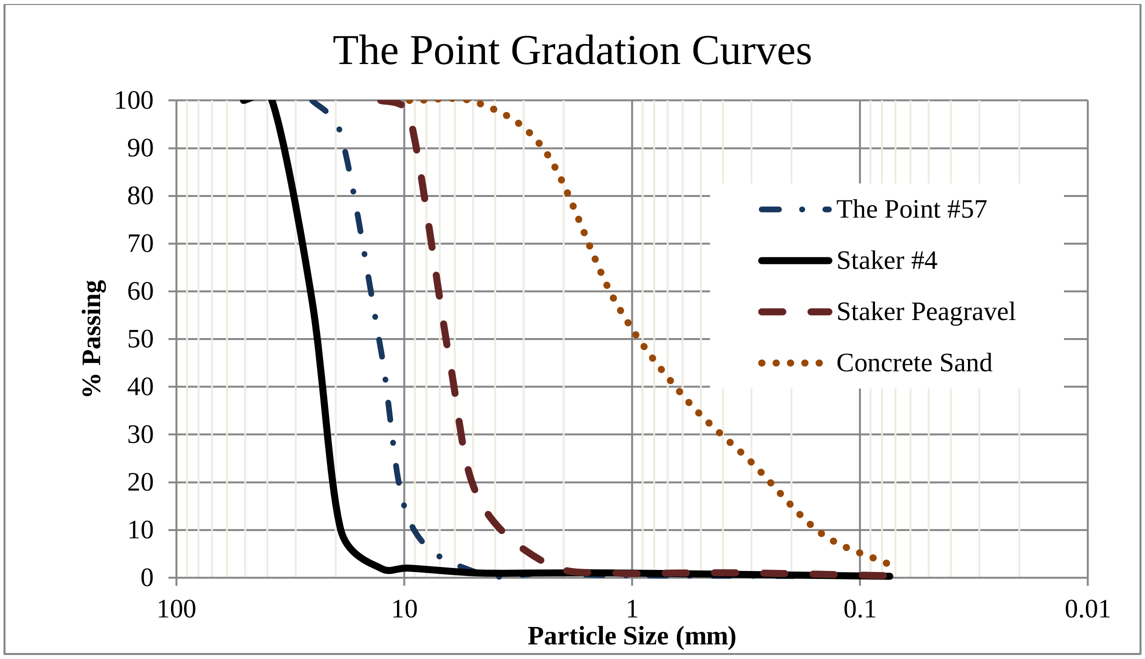
Harper

Aggregate Properties	NMAS	Bulk Specific Gravity SSD	Absorption Capacity
#67 Coarse Aggregate*	0.75"	2.67	1.06
#8 Coarse Aggregate*	0.5"	2.67	1.06
Natural Sand*	#4	2.65	1.15

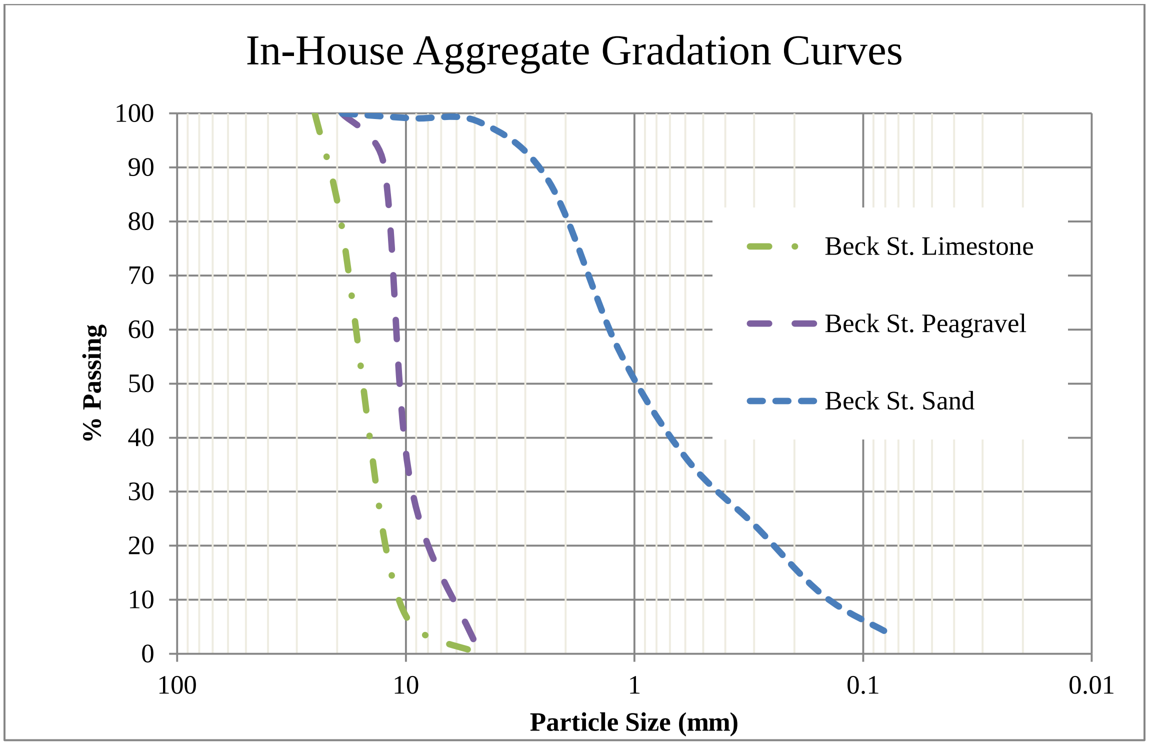
The Point

Aggregate Properties	NMAS	Bulk Specific Gravity SSD	Absorption Capacity
Staker East #57	0.75"	2.50	1.75
Staker West #57	0.75"	2.55	1.40
Staker East #4	1.5"	2.50	1.40
Staker West #4	1.5"	2.55	1.40
Staker East Sand	#4	2.60	1.10
Staker West Sand	#4	2.59	1.40
Staker East Peagravel	3/8"	2.50	1.90
Staker West Peagravel	3/8"	2.55	1.90

*Gradation Curve not available



East and West pit of The Point aggregates have the same particle distribution.



A.2 Cement and Fly Ash Properties

Material: Portland Cement

Type: ASTM C150 Type II-V

Supplier: Lafarge-Holcim Devil's Slide Plant

Chemical Properties (Cement)		
Item	Limit %	Result %
SiO2	-	20.4
Al2O3	6.0 Max	4
Fe2O3	6.0 Max	3.5
CaO	-	63.5
MgO	6.0 Max	2.7
SO3	2.3 Max	3
Loss on Ignition	3.0 Max	2.3
Insoluble Residue	0.75 Max	0.42
CO2	-	1.7
Limestone	5.0 Max	4.3
CaCO3 in Limestone	70 Min	89
Inorganic Processing Addition	5.0 Max	0
Bogue Estimates		
C3S	-	57
C2S	-	15
C3A	5 Max	5
C4AF	-	10
C3S + 4.75C3A	-	80.8
Equivalent Alkalies (%)	0.60 Max	0.55
Physical Properties (Cement)		
Item	Limit	Result
Air Content %	12 Max	7
Blaine Fineness (m2/kg)	260 Min	408
Autoclave Expansion % ASTM C151	0.80 Max	0.04
Initial Vicat (minutes)	45-375	113
Mortar Bar Expansion % ASTM C1038	-	0.01
Heat of Hydration 7 dys (kJ/kg)		75
Compressive Strength (psi)		
3 days	1450 Min	4390
7 days	2470 Min	5330

Material: Fly Ash
Type: ASTM C618 Class F
Supplier: Headwaters Resources Navajo

Chemical Properties (Fly Ash)		
Item	Limit %	Result %
SiO2	-	59.35
Al2O3	-	22.45
Fe2O3	-	4.68
Sum of Constituents	70 Min	86.48
SO3	5 Max	0.41
CaO	6.0 Max	5.07
Moisture	3 Max	0.06
Loss on Ignition	6 Max	6
Available Alkalies as Na2O	1.5 Max	1.38
Physical Properties (Fly Ash)		
Item	Limit %	Result %
Fineness, % retained on #325	34 Max	19.91
Water Requirement, % Control	105 Max	95
Autoclave Soundness	0.8 Max	0.01
Density		2.35
Strength Activity Index		
7 day, % of control	75 Min	89
28 day, % of control	75 Min	95

APPENDIX B. PROCEDURE FOR CEMENTOMETER^{TM}

B.1 Fine Aggregate (Sand) Preparation

Step 1: Place the sand in an oven for 24 hours to dry in order to insure complete evaporation of water from the surface and internal pores.

Step 2: Remove sample from oven and allow sample to cool down.

Step 3: Immerse sample in water for 24 hours to ensure full water saturation.

Step 4: Remove excess water from sample and prepare at SSD in accordance to ASTM C 128-01.

The sand sample is now at SSD condition.

B.2 Coarse Aggregate Preparation

Step 1: Place the coarse aggregate sample in an oven for 24 hours to dry in order to insure complete evaporation of water from the surface and internal pores.

Step 2: Remove sample from oven and allow to cool.

Step 3: Immerse sample in water for 24 hours to ensure full water saturation

Step 4: Remove excess water from the surface of sample in order to have sample at SSD condition.

The coarse aggregate sample is now at SSD condition.

Once the fine and coarse aggregates are conditioned, a proper weight for the mixture is batched and the mixing procedure is ready to start.

B.3 Mixing the sample

Step 1: Spray down inner dome to moisten drum.

Step 2: Remove any excess water and start revolving the mixer.

Step 3: Add 10% of the water and coarse aggregate into the drum.

Step 4: Add 50% of the fine aggregates and cement into the drum.

Step 5: Add 60% of the coarse aggregate and the remaining water until approximately ¼ to 1.3 of the water is remaining in the reservoir being used to contain the water.

Step 6: Add the remaining fine aggregate and cement to the drum followed by the remaining coarse aggregate and water.

Step 7: Let sample mix until a proper paste has been achieved

Step 8: Remove a sample of plastic concrete from the drum in order to take calibration measurements. Once the readings are obtained, return sample to mixer and add more water to reach next w/cm. Repeat steps 7 and 8.

After an even mixture is attained, the cementitious materials are added with the remaining water. Once a proper paste is achieved in accordance to ASTM C192/C192 M standard, a sample large enough to allow the probes in with sufficient clearance from all directions is removed and placed in a container that allows at least a 2 inch clearance around the meter's probes. After the calibration readings are obtained, the sample is returned to the mixer and additional water is added to achieve a 0.05 increase in w/cm. The addition of water procedure was repeated 9 times until the full range of calibration values were obtained.

APPENDIX C. EQUATIONS

C.1 Nomenclature

W = Weight

V = Volume

$\frac{w}{cm}$ = Water-to-cementitious ratio

UW = Unit Weight

AC = Absorption capacity of aggregate

WC = Water or moisture content in concrete sample

WT = Total water content in concrete sample

C.2 Adjustment to SSD

$$AC = \frac{W_{aggregate\ SSD} - W_{aggregate\ OD}}{W_{aggregate\ OD}} \times 100\%$$

where:

$W_{aggregate\ SSD}$ = Saturated surface dry weight of the aggregate

$W_{aggregateOD}$= Oven dried weight of the aggregate

Or alternatively:

$$W_{aggregate\ SSD} = \frac{(AC + 1)\ W_{aggregate\ OD}}{100\%}$$

Then the dosed w/cm or unadjusted w/cm displayed in Table 2.2 for mortar 2 as input into the user-program during calibration was calculated as:

$$Unadjusted\ \frac{w}{cm} = \frac{W_{batch\ water, aggregates\ OD}}{W_{cementitious}}$$

The adjusted w/cm or actual w/cm displayed in Figure 2.8 and Figure 2.12 is calculated as:

$$Actual\ \frac{w}{cm} = \frac{W_{batch\ water, aggregates\ SSD}}{W_{cementitious}} = \left(Unadjusted\ \frac{w}{cm}\right) - \frac{W_{absorbed\ water}}{W_{cementitious}}$$

or

$$Actual\ \frac{w}{cm} = \frac{W_{batch\ water, aggregates\ OD} * (1 - AC)}{W_{cementitious}}$$

where:

$$W_{batch\ water, aggregates\ SSD} = W_{batch\ water, aggregates\ OD} - W_{absorbed\ water}$$
$$= W_{batch\ water, aggregates\ OD} * (1 - AC)$$

$$W_{absorbed\ water} = W_{aggregate\ SSD} - W_{aggregate\ OD} = W_{batch\ water, aggregates\ OD} * AC$$

C.3 Volumetric Ratio

$$Volumetric\ Ratio = \frac{V_{Water}}{V_{Solids}}$$

where:

$$V_{Water} = \frac{W_{water}}{UW_{water}}$$

$$V_{Solids} = V_{Cementitious} + V_{Coarse\ Aggregates} + V_{Fine\ Aggregates}$$

C.4 AASHTO T318-02 Microwave Test Water-Cement Ratio Calculation

Repeated from the standard:

$$WC = \frac{W_{tray+cloth+original\ sample} - W_{tray+cloth+after\ microwaved\ sample}}{W_{tray+cloth+original\ sample} - W_{tray+cloth}} * 100\%$$

$$WT = WC * UW_{concrete}$$

Assumptions:

- Weight of tray and cloth combined was tared so as not to contribute to the weight measured of the original sample or after being microwaved.
- The original sample obtained for the microwave test is representative of the entire concrete mixture.
- All batch weights are reported for SSD condition of aggregates.
- Total water measured by the microwave method includes batched water, water that was absorbed into aggregates to make it SSD condition, plus any additional water added before hardening.

Additional equations to obtain "calculated w/cm":

$$\begin{aligned} W_{water\ in\ sample} &= W_{original\ sample} - W_{after\ microwaved\ sample} \\ &= W_{batched\ water,sample} + W_{additional\ water,sample} \end{aligned}$$

A scale factor for how small the sample is relative to the batched weights is:

$$SF = \frac{W_{original\ sample}}{\sum W_{each\ material\ as\ batched}}$$

$$Calculated\ \frac{w}{cm} = \frac{(W_{batched\ water} + W_{additional\ water} - W_{absorbed\ water})}{W_{cementitious}}$$

$$= \frac{W_{water\ in\ sample} + SF * \sum(AC_i * W_{aggi})}{SF * W_{cementitious}}$$

Example calculation for 0.4 w/cm actual mixture tested needs to have the following information given:

Mixture Proportions (SSD condition)		
	AC	Batch Weights (lb)
Cement		19.7
Fly Ash		3.9
Sand	1.9%	25.65
Coarse Agg1	0.43%	9.9
Coarse Agg2	0.28%	29.7
Water		9.44

ASTM C138 Unit Weight Test

Concrete Unit Weight (lb/cf)	144.8

AASHTO T318-02 Microwave Test Values

Original Sample (lb)	3.895
Sample After Microwaved (lb)	3.505

The following calculations can then be made:

Water Content *WC* = (3.895 – 3.505) / (3.895) *100 = **10.02%**

Total Water *WT* = (10.02%*144.8*27) = **392 pcy**

Total batch weights $\sum W_{each\ material\ as\ batched}$= (19.7+3.9+25.65+9.9+29.7+9.44) = **98.29 lb**

Total cementitious $W_{cementitious}$= (19.7+3.9) = **23.6 lb**

Water absorbed by aggregate

Sand	1.9%*25.65 = 0.4874 lb
Coarse Agg1	0.43%*9.9 = 0.0426 lb
Coarse Agg2	0.28%*29.7 = 0.0832 lb
$\sum(AC_i * W_{aggi})$	= 0.6131 lb

Water in sample $W_{water\ in\ sample}$ = (3.895 – 3.505) = **0.39 lb**

Scale Factor SF = (0.39) / (98.29) = **0.0396**

Actual w/cm ratio = (9.44) / (23.6) = 0.40

Calculated w/cm ratio = (0.39 – 0.0243*0.0396) / (0.0396*23.6) = **0.391**

APPENDIX D. STATISTICS

D.1 Absolute Difference of Calibration Data to Actual W/C

Difference of any given $\frac{\mathrm{w}}{\mathrm{cm}}$ mode output value to Actual $\frac{\mathrm{w}}{\mathrm{cm}}$:

$$\mathbf{x}_{i,mode} = \boldsymbol{w/c_{Actual}} - \boldsymbol{w/c_{i,mode}}$$

Note if the mode output is "out of range" these calculation will be omitted.

Absolute Maximum Difference for a mode output value at a given $\frac{\mathrm{w}}{\mathrm{cm}}$:

$$\boldsymbol{D_{max}} = \max_{\boldsymbol{given\ w/c}} \left|\mathbf{x}_{i,mode}\right|$$

Absolute Minimum Difference for a mode output value at a given $\frac{w}{\mathrm{cm}}$:

$$\boldsymbol{D_{min}} = \boldsymbol{min}\left|\mathbf{x}_{i,mode}\right|$$

Average Absolute Difference for a mode output value at a given $\frac{w}{\mathrm{cm}}$:

$$\boldsymbol{D_{ave}} \quad \frac{\sum\left|\mathbf{x}_{i,mode}\right|}{\boldsymbol{N_{mode,given\ w/c}}}$$

where $N_{mode,given\ w/c}$ = number of readings corresponding to that Actual w/cm not including any "out of range" values.

Square Error $= \left(\mathrm{x}_{i,mode}\right)^2$

Sum of Square Error $\mathbf{SSE} = \sum\left(\mathbf{x}_{i,mode}\right)^{\mathbf{2}}$

Sample Calculation for User-Program Mode value measurements at a 0.35 w/c actual content:

Actual w/c_{Actual}	User-Program $w/c_{i,User}$	Difference $x_{i,User}$	Absolute Difference $\lvert x_{i,User} \rvert$	Square Error $(x_{i,mode})^2$
0.35	0.30	0.05	0.05	0.0025
0.35	0.67	-0.32	0.32	0.1024
0.35	0.60	-0.25	0.25	0.0625
0.35	0.62	-0.27	0.27	0.0729
0.35	0.64	-0.29	0.29	0.0841
0.35	OOR			
0.35	0.65	-0.3	0.3	0.09
0.35	0.37	-0.02	0.02	0.0004
0.35	0.35	0	0	0
0.35	0.64	-0.29	0.29	0.0841
0.35	0.61	-0.26	0.26	0.0676
0.35	0.35	0	0	0
0.35	0.36	-0.01	0.01	0.0001
0.35	0.67	-0.32	0.32	0.1024
0.35	0.62	-0.27	0.27	0.0729
0.35	0.65	-0.3	0.3	0.09
0.35	0.58	-0.23	0.23	0.0529
0.35	0.65	-0.3	0.3	0.09
0.35	0.60	-0.25	0.25	0.0625

For this data set of 0.35 w/cm ratios, the following can be calculated:

D_{max}
$= \max_{0.35}(0.05,0.32,0.25,0.27,0.29,0.30,0.02,0.00,0.29,0.26,0.00,0.01,0.32,0.27,0.30,0.23,0.30,0.25)$

= 0.32

D_{min}

$= \min_{0.35}(0.05,0.32,0.25,0.27,0.29,0.30,0.02,0.00,0.29,0.26,0.00,0.01,0.32,0.27,0.30,0.23,0.30,0.25)$

= 0.00

D_{ave}

=(0.05+0.32+0.25+0.27+0.29+0.3+0.02+0+0.29+0.26+0+0.01+0.32+0.27+0.3+0.23+0.3+0.25) / 18

= 0.2072

(again note, the OOR reading is not included in the average difference)

SSE

=0.0025+0.1024+0.0625+0.0729+0.0841+0.09+0.0004+0.00+0.0841+0.0676+0.00+0.0001+0.1024+0.0729+0.900+0.0529+0.090+0.0625

= 1.0373

D.2 T-test Calculations of Entire Data Set Values and W/CM Differences

Sample calculation for entire data set of Type I Mode output concrete mixture validation measurements T-Test statistics:

Sample Size N_{Actual} = 157

Sample Size $N_{Type\ I}$ = 156

$$Mean\ Actual\ \frac{\mathrm{w}}{\mathrm{cm}} Values:\ \mu_{Actual} = \frac{\sum Actual\ \frac{w}{cm}}{N_{Actual}} = \frac{64.64}{157} = \mathbf{0.4117}$$

$$Mean\ Type\ I\ \frac{\mathrm{w}}{\mathrm{cm}} Values:\ \mu_{Type\ I} = \frac{\sum Type\ I\ \frac{w}{cm}}{N_{Type\ I}} = \frac{62.96}{156} = \mathbf{0.4036}$$

$$Standard\ Deviation\ of\ Value\ \sigma_{Actual} = \sqrt{\frac{1}{N_{Actual}} * \sum_{i=1}^{N_{Actual}} \left(w/c_{\ i,Actual} - \mu_{Actual}\right)^2}$$

$$= \mathbf{0.0439}$$

$$Standard\ Deviation\ of\ Value\ \sigma_{Type\ I} = \sqrt{\frac{1}{N_{Type\ I}} * \sum_{i=1}^{N_{Type\ I}} \left(w/c_{\ i,Type\ I} - \mu_{Type\ I}\right)^2}$$

$$= \mathbf{0.0247}$$

D.3 T-test for a single data set

D.3.1 <u>All mode outputs to actual w/cm</u>

Mean Difference $\mu_{Actual} - \mu_{Type\ I} = 0.4117 - 0.4036 = \mathbf{0.00813}$

$$Pooled\ Standard\ Error\ Sp_{all,Type\ I} = \sqrt{\frac{(\sigma_{Actual})^2(N_{Actual} - 1) + (\sigma_{TypeI})^2(N_{Type\ I} - 1)}{(N_{Actual} - 1) + \left(N_{Type\ I} - 1\right)}}$$

$$= \sqrt{\frac{(0.0439)^2(156) + (0.0247)^2(155)}{(156) + (155)}} = \mathbf{0.0356}$$

$$Tvalue = \frac{\mu_{Actual} - \mu_{Type\ I}}{Sp_{all,Type\ I}\sqrt{\frac{1}{N_{Actual}} + \frac{1}{N_{Type\ I}}}} = \frac{0.00813}{0.0356\sqrt{\frac{1}{157} + \frac{1}{156}}} = \mathbf{2.0198}$$

$$Degrees\ of\ Freedom = \frac{\left(\frac{(S_{Actual})^2}{(N_{Actual})} + \frac{(S_{TypeI})^2}{(N_{TypeI})}\right)^2}{\frac{1}{N_{Actual} - 1}\left(\frac{(S_{Actual})^2}{(N_{Actual})}\right)^2 + \frac{1}{N_{TypeI} - 1}\left(\frac{(S_{TypeI})^2}{(N_{TypeI})}\right)^2} = \mathbf{246}$$

This t-value and degrees of freedom correspond to p-value = **0.0445** found using statistical software.

D.3.2 Mode outputs to each actual w/cm

For a 0.35 w/cm ratio and Type I mode:

Mean Difference $\mu_{Actual,0.35} - \mu_{Type\ I,0.35} = 0.35 - 0.39947 = \mathbf{0.04947}$

$$Standard\ Error\ SE_{0.35,Type\ I} = \sqrt{\frac{(S_{TypeI,0.35})^2}{N_{Type\ I,0.35}}} = \sqrt{\frac{(0.02321)^2}{(19)}} = \mathbf{0.00532}$$

$$Tvalue = \frac{\mu_{Actual,0.35} - \mu_{Type\ I,0.35}}{SE_{0.35,Type\ I}} = \frac{0.04947}{0.00532} = \mathbf{9.29}$$

$$Degrees\ of\ Freedom = N_{Type\ I,0.35} - 1 = \mathbf{18}$$

This t-value and degrees of freedom correspond to p-value = **2.73982E-08** found using statistical software.

D.4 Individual W/CM Ratio Data Sets and Confidence Intervals

These were derived for each actual w/cm ratio validated of concrete mixtures. Similar equations to that above are used, except the sample size of the data sets is smaller.

$$Confidence\ Interval = \bar{X}_{mode,given\ w/cm} \pm T_{alpha=0.05,\ \ df\ of\ dataset} \times SE_{dataset}$$

The confidence interval is drawn for a level of significance of 0.05 corresponding to 95% confidence as follows:

$$T_{alpha=0.05,\ \ df=18} = \mathbf{2.1009}$$

$Confidence\ Interval = 0.39947\ \pm 2.1009\ \times 0.00532$ = **(0.388, 0.411)**